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WELDABILITY OF FORMABLE SHEET TITANIUM ALLOY - Ti-15V-3Cr-3Al-3Sn

Bell Aerospace Textron
Buffalo, New York 14240

December 1978

Approved for public release; distribution unlimited.

AIR FORCE MATERIALS LABORATORY
Air Force Wright Aeronautical Laboratories
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Wright-Patterson Air Force Base, Ohio 45433

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This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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Gas-Tungsten-Arc (GTA) and Electron Beam (EB) fusion welding process parameters were established for Ti-15V-3Cr-3Al-3Sn alloy sheet in 0.050-, 0.100- and 0.300-inch thicknesses. The material, purchased from Timet, was characterized by mechanical testing in the following conditions: solution annealed and solution annealed and aged at 900 and 950°F for eight hours. Solution annealed material is very ductile and formable. Aging response of base metal shows that 150 to 170 ksi minimum yield strengths can be achieved. GTA and EB welds were made using a square butt joint configuration in the 0.050- and 0.100-inch thickness. A "V" joint configuration was used to weld

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20. ABSTRACT

0.100-inch thick material with filler wire using the GTA process. 0.300-inch material was welded with the EB process only. All weldments were made using production equipment and there were no anomalies in welding this material, X-ray and dye penetrant tests showed that weldments were crack-free and within porosity limits. Bend and tensile tests made on weldments in the as-welded condition were very ductile and compared favorably to the ductility of solution annealed base metal. Aging response of welded specimens, tensile tested in both longitudinal and transverse directions, was similar to base metal and properties compared favorably to base metal properties. Notched tensile strengths, fracture toughness, and crack growth rates all indicate that Ti-15V-3Cr-3Al-3Sn weldments are satisfactory for structural applications.

FOREWORD

This final technical report covers the work performed under Contract F33615-75-C-5232 from 1 May 1977 through 31 August 1978. This contract with Bell Aerospace Textron was initiated under Project 799-5. The program is being administered under the technical direction of Mr. Kenneth L. Kojola, Metals Branch, LTM, Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson AFB, Ohio 45433.

The subject program is being conducted by the Manufacturing Engineering Department of Bell Aerospace Textron. Work described in this report was accomplished under the direction of Mr. A.E. Leach, Program Manager. Phase III weldability investigations were under the direction of Mr. J.D. McDonough. Mechanical tests and metallographic analyses were made by Messrs. E.J. King, W.L. Burch, and H. Kammerer. The program is under the general direction of Mr. R.W. Hussa, Vice President, Manufacturing.

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SECTION I

INTRODUCTION

The weldability program accomplished under this contract and detailed in this report is a continuation of Air Force sponsored evaluations of formable sheet titanium alloys for aerospace applications. The Ti-15V-3Al-3Cr-3Sn alloy, along with other candidate compositions, was originally produced as sheet by TIMET under AFML Contract F33615-74-C-5063. These alloys were subjected to rigorous evaluations of formability characteristics and properties and the Ti-15V-3Al-3Cr-3Sn was chosen as the best composition for further exploitation. This early work is reported in AFML-TR-76-45, (1).

An evaluation of room temperature shear spinnability of Ti-15V-3Al-3Cr-3Sn sheet was conducted under this contract in a prior program as part of the overall Air Force formability investigation. The alloy proved to have extremely desirable shear spinnability with cold reductions of over 80% being readily achieved. In fact, it was recognized as an excellent candidate for fabrication into aerospace pressure vessels by the shear spin/form process, a new method for low-cost fabrication of titanium alloy pressure vessels. Its relative freedom from distortion during heat treatment, because it is air cooled from solution temperatures, makes it highly suitable for pressure vessels and other high strength structural members. The shear spinning investigations are reported in AFML-TR-77-88, (2).

Good weldability and excellent properties in the welded conditions are important requirements for titanium alloys in pressure vessel applications, as they are in many other structural applications. The Ti-15V-3Al-3Cr-3Sn alloy was relatively new and little was known about its weldability, so an additional phase was added to this contract to establish its weldability characteristics. Gas-Tungsten - Arc (GTA) and Electron Beam (EB) processes were investigated for producing structurally sound welds in 0.050, 0.100, and 0.300 inch thick sheet and plate. Mechanical properties and metallurgical characteristics were determined for each process and condition of material and were compared to base metal properties.

SECTION II
MATERIAL

Ti-15V-3Cr-3Al-3Sn sheet and plate was procured for this program from Timet. The initial procurement was material produced on Contract USAF F33615-74-C-5063 and was from a laboratory heat, V5031. This material was used to establish welding conditions for 0.050- and 0.100-inch thick titanium alloy sheet. The remaining material procured was from a production heat, P2360, and was used to establish welding conditions for 0.300-inch thick alloy plate. This heat, P2360, was used for "Optimum Weldment Characterization" in all three material thicknesses. The identity of this material is:

Vendor	Heat No.	Condition	Gage and Size
Timet	V5031	Cold Rolled Soln Ann	0.050 in. x 5.625 in. x 71 ft (8 ft multiples)
Timet	V5031	Cold Rolled Soln Ann	0.100 in. x 5.625 in. x 55 ft (8 ft multiples)
Timet	P2360	Cold Rolled Soln Ann	0.050 in. x 36 in. x 96 in.
Timet	P2360	Cold Rolled Soln Ann	0.100 in. x 36 in. x 96 in. (2 pcs)
Timet	P2360	Hot Rolled Soln Ann	0.300 in. x 36 in. x 72 in. (2 pcs)

Table 1 gives the chemical composition of this material and Tables 2-5 give the base metal mechanical properties in the solution annealed and aged condition.

Heat V5031 material, received in 8 foot strips 5-5/8 inches wide, was generally acceptable dimensionally. The gage thickness in each size was within specification (±0.005-inch for 0.050 gage and ±0.009-inch for 0.100 gage), and there was only one 8 foot length too out-of-flat to cut into weld specimens. Most of the material was used for initial well parameter establishment.

The 0.050 and 0.100-inch thick material received from Heat P2360 was excellent. Thickness, flatness, and surface condition were well within specification limits or comparable to other standard titanium sheet product. The 0.300-inch thick plate, although within the mill tolerance of 11/16 inch for flatness, was near the upper limit; this made it difficult to machine weld specimens for close tolerance electron beam welding.

Characterization tests were conducted on all of the material received and are reported in Tables 2-5. Material tested in the solution annealed condition for both heats and all thicknesses indicate the material to be very ductile and having excellent formability. Aging response indicates that 150 ksi minimum yield strength, for which this material was designed, can easily be achieved. 950°F for 8 hours appears to be an excellent treatment for all gages of heat V5031 and the 0.100-inch thick sheet of heat P2360. A slightly lower temperature (probably 925°) would be needed for a 150 ksi minimum yield strength in the 0.050- and 0.300-inch thick plate of heat P2360. Bend performance in the solution annealed condition is excellent. The highest bend values (poorest bend) were obtained in the highest strength material (aged at 900°F) as expected, with bend performance improving as strength level drops.

TABLE 1
CHEMICAL COMPOSITION - Ti-15V-3Cr-3Al-3Sn MATERIAL

VENDOR ANALYSIS

Vendor	Heat No.*	Gage	Fe	N	H_2	O_2	V	Cr	Al	Sn	C
Timet	V5031	0.050	0.24	0.025	0.009	0.11	15.0	3.1	2.9	3.1	-
		0.100	0.24	0.025	0.007	0.11	15.0	3.1	2.9	3.1	-
Timet	P2360	0.050	0.16	0.014	0.017	0.11	15.0	3.2	3.2	3.1	0.015
		0.100	0.16	0.014	0.008	0.11	15.0	3.2	3.2	3.1	0.015
		0.300	0.16	0.014	0.008	0.13	15.0	3.2	3.2	3.1	0.015

*Heat No. V5031 is a laboratory heat. This material was used for the initial weld parameter establishment.
Heat No. P2360 is a production heat. This heat was used for Task IV and will be used for Task V - "Optimum Weldment Characterization".

TABLE 2
BASE METAL MECHANICAL PROPERTIES

Heat No.	Gage (in.)	Condition	Dir	Ult Strength ksi	Ult Strength MPa	Yield Strength ksi	Yield Strength MPa	Elongation % 2 in. or 50 mm	Longitudinal Bend (XT) Pass	Longitudinal Bend (XT) Fail
V5031	0.050	Soln Annealed*	L	115	792	110	758	13	0.6	–
			L	116	799	112	772	13		
V5031	0.050	Soln Annealed +	L	169	1164	152	1047	10	3.7	3.5
		Age - 950°F - 4 hr	L	167	1151	146	1006	11		
V5031	0.100	Soln Annealed	L	113	779	112	772	18		
			L	112	772	112	772	18	0.6	–
V5031	0.100	Soln Annealed	L	191	1316	177	1220	7	4.4	4.3
		+ Age - 950°F - 4 hr	L	172	1185	158	1089	11		

*Solution Anneal - 1450°F - 20 minutes - Air cool

TABLE 3
BASE METAL MECHANICAL PROPERTIES

Heat No.	Gage (In.)	Condition	Dir	Ult. Strength ksi	Ult. Strength MPa	Yield Strength ksi	Yield Strength MPa	Elongation % 2 in. or 50 mm	Longitudinal Bend (XT) Pass	Longitudinal Bend (XT) Fail
P2360	0.050	Soln Annealed* (Supplier Data)	L	111	765	107	737	14	2	
			L	111	765	106	730	18	2	
			T	112	772	108	744	17		
			T	113	779	108	744	14		
P2360	0.050	Soln Ann + 950°F Age - 8 hr (Supplier Data)	L	165	1137	145	999	10		
			T	-	-	-	-	-		
P2360	0.050	Soln Ann + 1000°F Age - 8 hr (Supplier Data)	L	149	1027	130	896	12		
			T	148	1020	129	889	9		
P2360	0.050	Soln Ann + 1050°F Age - 8 hr (Supplier Data)	L	137	944	119	820	12		
			T	-	-	-		-		
P2360	0.050	Soln Annealed	L	115	792	106	730	12	0.6	
			L	116	799	109	751	13	0.6	
			T	116	799	111	765	15		
			T	115	792	110	758	15		
P2360	0.050	Soln Annealed + Age - 900°F - 8 hr	L	180	1240	160	1102	9	7.5	6.3
			L	182	1254	163	1123	10	8.8	7.5
			T	185	1275	164	1130	9		
			T	184	1268	166	1144	9		
P2360	0.050	Soln Annealed + Age - 950°F - 8 hr	L	162	1116	139	958	10	4.7	4.5
			L	163	1123	144	992	11	5.0	4.9
			T	164	1130	146	1006	10		
			T	165	1137	145	999	10		
P2360	0.050	Soln Annealed + Age 1000°F - 8 hr	L	149	1027	133	916	12	3.8	3.6
			L	148	1020	130	896	12	4.4	4.2
			T	151	1040	137	944	12		
			T	151	1040	134	923	13		

*Solution Annealed - 1450°F - 20 minute - air cooled

TABLE 4
BASE METAL MECHANICAL PROPERTIES

Heat No.	Gage (in.)	Condition	Dir.	Ult Strength ksi	Ult Strength MPa	Yield Strength ksi	Yield Strength MPa	Elongation % 2 in. or 50 mm	Longitudinal Bend (XT) Pass	Longitudinal Bend (XT) Fail
P2360	0.100	Soln Annealed* (Supplier Data)	L	108	744	105	723	17		
			L	111	765	107	737	20		
			T	111	765	107	737	15		
			T	112	772	108	744	18		
P2360	0.100	Soln Annealed	L	115	792	109	751	18	0.6	
			L	115	792	110	758	18	0.6	
			T	116	799	111	765	17		
			T	115	792	112	772	17		
P2360	0.100	Soln Annealed + Age - 900°F - 8 hr	L	189	1302	170	1171	11	10	7.5
			L	189	1302	167	1151	12		10
			T	191	1316	172	1185	8		
			T	189	1302	170	1171	8		
P2360	0.100	Soln Annealed + Age - 950°F - 8 hr	L	172	1185	153	1054	10	6.6	6.3
			L	172	1185	153	1047	10	7.5	7.4
			T	175	1206	158	1089	10		
			T	175	1206	157	1082	11		
P2360	0.100	Soln Annealed + Age - 1000°F - 8 hr	L	158	1089	141	971	14	3.1	3.0
			L	158	1089	141	971	14	4.4	3.0
			T	156	1075	138	951	12		
			T	155	1068	136	937	11		

*Solution Annealed - 1450°F - 20 minutes - Air Cooled

TABLE 5
BASE METAL MECHANICAL PROPERTIES

Heat No.	Gage (in.)	Condition	Dir	Ult Strength ksi	Ult Strength MPa	Yield Strength ksi	Yield Strength MPa	Elongation 2 in. or 50 mm
P2360	0.300	Soln Annealed Supplier Data	L	117	806	112	772	18
			L	114	786	109	751	22
			T	115	792	110	758	22
			T	118	813	112	772	18
P2360	0.300	Soln Annealed	L	112	772	109	751	21
			L	111	765	110	758	22
P2360	0.300	Soln Annealed + Age 950°F - 8 hr	L	162	1116	145	999	11
			L	161	1109	145	999	13

*Soln Anneal - 1450°F - 20 minutes - Air Cool

SECTION III

WELDING PARAMETER ESTABLISHMENT

The welding processes used under this program were Gas Tungsten Arc (GTA) and Electron Beam (EB). These processes are presently used at Bell to weld titanium alloys and it was decided to use production equipment to give a direct comparison to the production weldability of other alloys.

The GTA welding equipment consists of a P&H Power Supply, Heliweld Automatic Weld Head, Linde Machine Carriage, Air Line Welding Positioner and a Linde Wire Feed System. The Electron Beam welder is a Hamilton Standard Model W-2 having 6.0 kilowatts maximum power. The equipment has a beam defocus and a circle generator for beam oscillation or deflection where required.

The material, after receiving inspection, was sheared to the specified sample sizes. All weld samples were 8 inches long. To conserve material, the welds to be tested in the longitudinal direction were sheared into specimens 2 x 8 inches x thickness and the transverse weldments were sheared into specimens 4 x 8 inches x thickness. All welding was done on the 8 inch length of the specimen which was also the rolling direction of the sheet and plate (see Figure 1). For longitudinal weld tests, one welded sample was required for each test but three transverse test

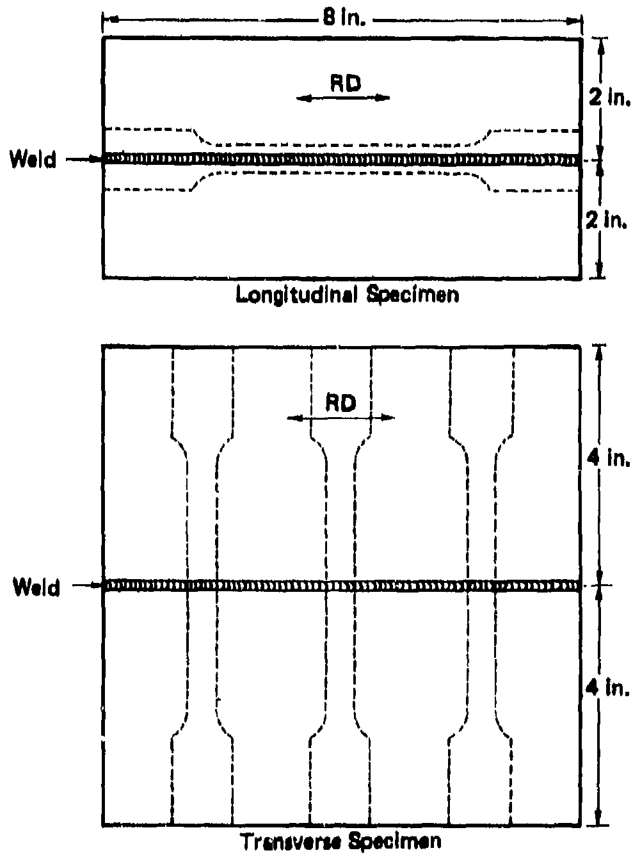


Figure 1. Weld Test Specimen

specimens were removed from each welded sample. A minimum of six specimens, three longitudinal and three transverse, were tested for each material condition. The square butt joint configuration was utilized on the 0.050, 0.100- and 0.300-inch thick material. This joint prep was achieved by milling the 8 inch long edge on all samples. A "V" groove joint prep was used on the 0.100-inch thick material with the use of filler wire and the GTA process. The "V" groove used was a 60° included angle with an 0.020-inch land and a zero root opening. The "V" groove was produced by a milling machine operation

After pre-weld treatment, such as heat treatment or machining the weld prep area, parts were chemically cleaned in a production facility using the following sequence: akaline clean, water rinse, nitric-hydrofluric pickle, demineralized water rinse, forced air dry, and bag. Samples were handled with lint-free gloves to avoid contamination prior to welding.

1. EB WELDING

EB weld parameters investigated during the program were those having major effects on weld properties and quality. Specific EB weld parameters investigated were: voltage (kV), amperage (mA), workpiece travel speed (ipm), electron beam deflection (circle generation and defocus), electron beam guns (S-32 and R-40), and electron beam magnetic field deflections. The objective was to produce satisfactory welds using minimum heat inputs, expressed in Joules per inch.

Satisfactory EB welds were those which met the following characteristics:

1) Penetration - Weld joints to exhibit 100% penetration.

2) Surface Condition - Surface to be smooth and free of defects and not exhibit surface depressions in excess of 5% of the weld joint thickness.

3) Porosity - Radiographic examination not to reveal pores greater than 0.015 inch.

EB welding activities included establishment of satisfactory weld schedules for each material thickness and subsequent NDT, mechanical tests, and metallurgical evaluation. Test results determined whether EB weld schedules were satisfactory or if refinements were required to optimize parameters for the testing phase of the program. A minimum of four panels of each material thickness were EB welded for testing.

A weld fixture was designed and fabricated to EB weld all thicknesses involved. Figure 2 illustrates the weld fixture and its holding features. Provisions were made for top hold down as well as side force. Clearance was provided underneath for weld spatter and bottom nugget formation.

a. Task II - 0.050-Inch Thick Sheet Welding

The initial weld parameter study was done with bead on plate welds. This method gave approximate voltage, amperage, travel speed and weld shape required for a full penetration weld. It was determined, for the 0.050-inch thick material, that the S-32 gun, using a sharp focus and deflecting the beam to an 0.040 inch diameter circle gave a well shaped weld. Holding a constant 100 kV setting, weld currents were varied to give the full penetration weld required. Initially, a two pass weld method was employed to obtain good weld penetration and a smooth top surface. The first pass was to obtain 100% penetration and satisfactory bottom nugget formation and the second pass was a smoothing pass to produce a satisfactory top surface. Before welding test panels, how-

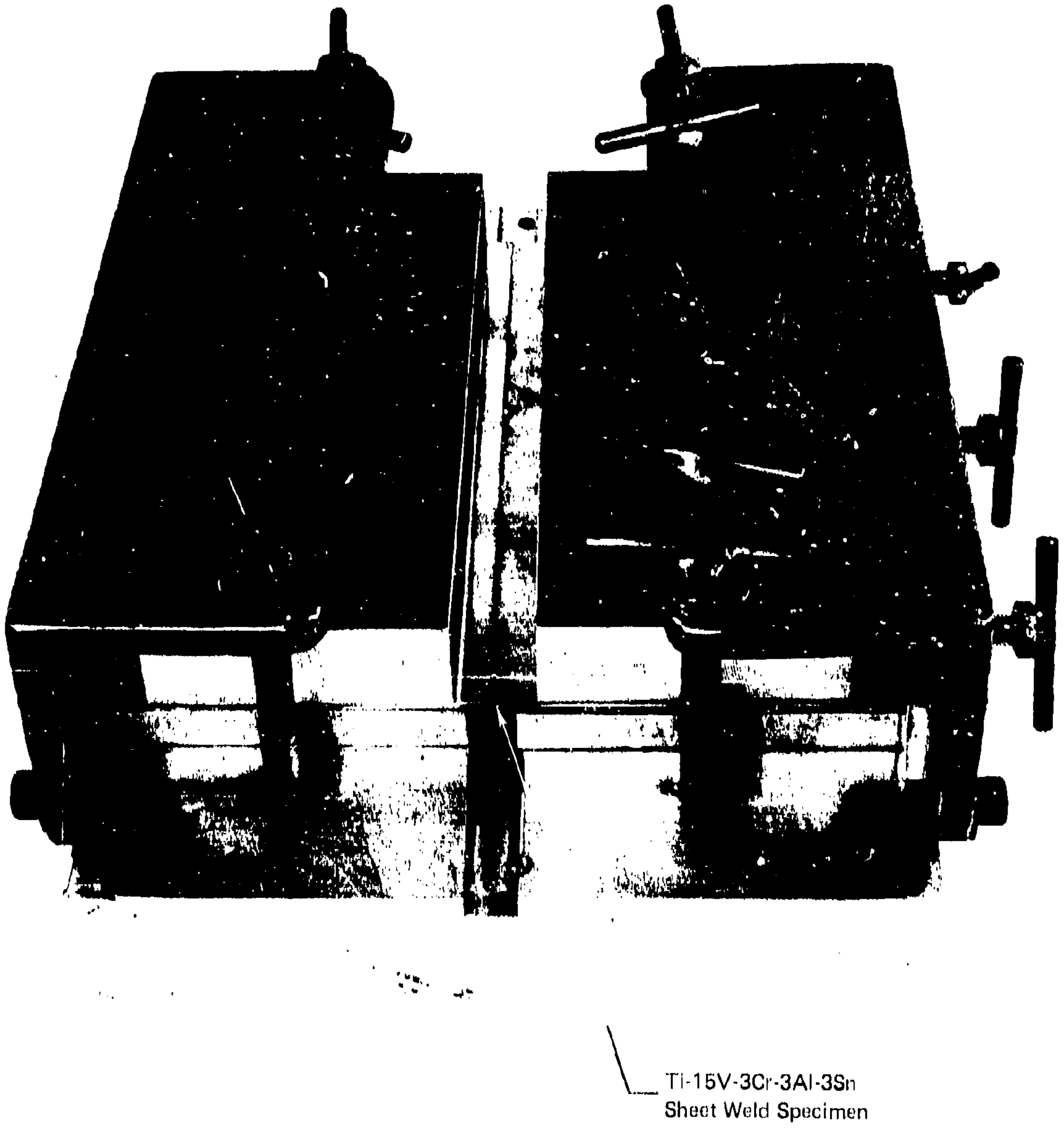


Figure 2. Weld Fixture - Electron Beam

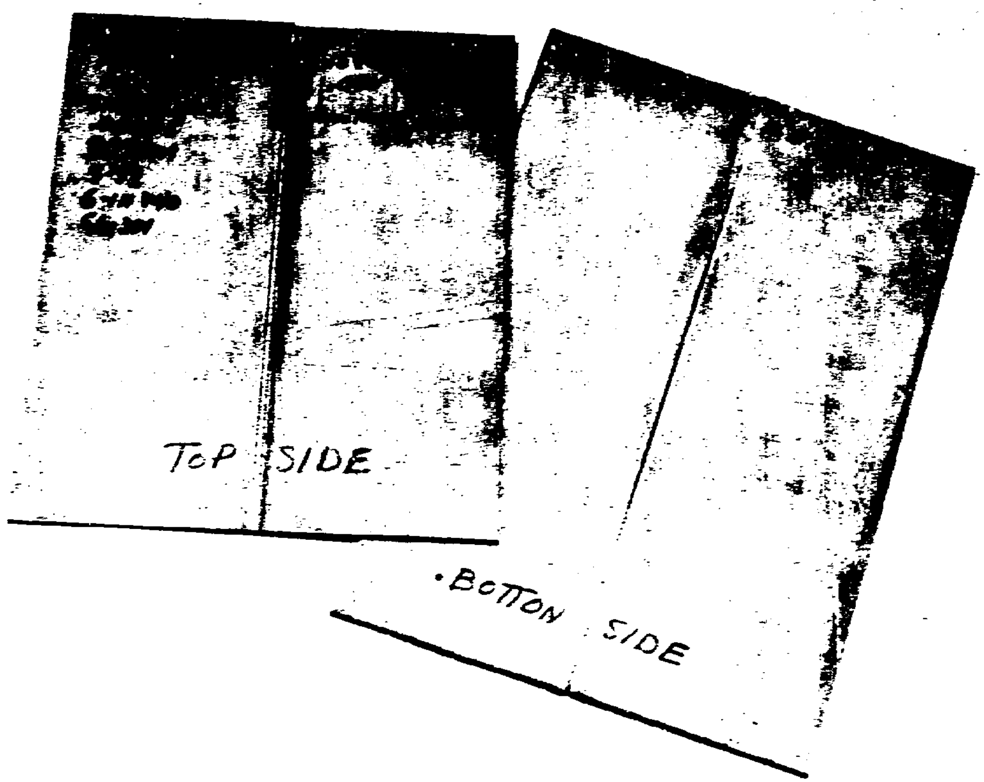


Figure 3. Electron Beam (EB) Weld Sample

ever, an unsatisfactory condition was found resulting from the two pass method. The welded panels distorted to a bow of about 0.060 inch in 4 inches. Distortion was found to be caused by the smoothing pass and was reproducible regardless of restraint during welding. It was then decided to EB weld the joint in a single pass by deflecting the beam to an 0.040-inch diameter circle to widen the fusion zone and obtain complete weld joint penetration. Satisfactory results were obtained and the smoothing pass was not required. Table 6 shows the EB weld parameters used in this task. The specimens used for tensile and bend tests were welded with parameters designated A-5. Each panel was tack welded first. Tack welds were intermittent, about 0.5 inch long. The parameters were the same for tack welding, except a setting of 1 mA was used. Figure 3 shows a typical EB weld in 0.050-inch thick sheet.

b. Task III - 0.100-Inch Thick Sheet Welding

The experience derived from EB welding on the 0.050-inch thick material proved valuable in that no attempt was made to use the double pass method in welding the 0.100-inch thick material. However, the R-40 gun was used, which has a softer or broader beam to help control surface depressions. We were able to develop a satisfactory weld that met all of the specified characteristics with only a few samples. Specimens were again tacked intermittently using a 2 mA setting with all other parameters the same. The parameters used for weld process establishment and for welding the tensile and bend test specimens are shown in Table 7.

c. Task IV - 0.300-Inch Thick Plate Welding

It was anticipated that with the heat input (joules/inch) required to weld a 0.300-inch thick material, changes would be made from previous parameters used on the 0.050- and 0.100-inch thick sheet. These parameters are given in Table 8 and each sample and change in parameters will be discussed in detail.

Sample SA-10 shows the initial parameters used, which were based on prior experience in EB welding thick titanium plate. It will be noted that a defocused beam was used for all of these samples. This is necessary at higher power levels to prevent expulsion craters in the top of the weld bead. Full penetration was not achieved with sample SA-10, nor was it achieved in sample SA-11 with a slight increase in welding current. Sample SA-12 with an increase in both voltage and current had the desired 100% penetration, but the top of the weld was slightly undercut.

The higher voltage was retained and returning the current to 12 milliamperes in sample SA-13 again failed to achieve full penetration. Fourteen milliamperes in sample SA-14 accomplished 100% penetration and this bead-on-plate sample had a good visual appearance. However, these same weld conditions in making a butt weld (sample SA-15) resulted in excessive drop through and undercutting in the top of the weld. At this point, the beam was defocused still further to avoid the metal expulsion which occurred in previous samples whenever 100% penetration was obtained. Some undercutting (sample SA-16) was still experienced but a slight reduction in current reduced this to a level which was almost acceptable (sample SA-17). A secondary cosmetic pass using a circle generator was then used with the above parameters to produce a more acceptable top in the EB weld bead (sample SA-18). Sample SA-19 was welded with a still lower current and the cosmetic smoothing pass produced a weld bead which was completely acceptable visually. The parameters used for sample SA-19 were then used for test panels.

This material, Ti-15V-3Cr-3Al-3Sn, in both sheet and plate and in the solution annealed and solution annealed and aged condition is considered readily weldable. The EB weld parameters used for the various thicknesses are very similar to those used for welding other titanium alloys. We

TABLE 6
EB WELD PROCESS PARAMETERS - Ti-15V-3Cr-3Al-3Sn
-0.050 IN. THICK MATERIAL

Sample Number*	Type of Weld**	kV	mA	Focus	Circle Generator Dia. (in.)	Weld Speed (ipm)	Work Dist. (in.)	Gun	Heat Input (Joules/in.)	Penetration %	Remarks
SA-1	BOP	100	2.4	Sharp	0.040	15	6	S-32	960	100	Slight top concavity.
SA-2	BOP	100	2.8	Sharp	0.040	15	6	S-32	1120	100	Top concave.
SA-3	Butt	100	2.2	Sharp	0.040	15	6	S-32	880	100	Top concave.
SA-4	Butt	100	2.2	+3 Def.***	0.040	15	6	S-32	880	100	Slight top concavity.
SA-5	Butt	100	2.2	+5 Def.	0.040	15	6	S-32	880	100	Slight top concavity.
A-1	Butt	100	2.2	+11 Def.	0.040	15	6	S-32	880	100	Slight top concavity.
A-2	BOP	100	4.5	Sharp	0.040	30	6	S-32	900	100	Top concave.
A-3	BOP	100	3.2	Sharp	0.040	30	6	S-32	640	100	Top concave.
A-4	BOP	100	2.3	Sharp	0.040	30	6	S-32	460	85	No top concavity; lack of penetration.
A-5	Butt	100	2.4	Sharp	0.040	30	6	S-32	560	100	Satisfactory weld geometry.

*SA - Solution Annealed - Before Welding
*A - Solution Annealed and Aged - Before Welding
**BOP - Bead on Plate
**Butt - Square butt joint
***Deflection (dial setting)

TABLE 7
EB WELD PROCESS PARAMETERS - Ti-15V-3Cr-3Al-3Sn
-0.100-IN. THICK MATERIAL

Sample Number*	Type of Weld	kV	mA	Focus	Circle Generator dia. (in.)	Weld Speed (ipm)	Work Dist. (in.)	Gun	Heat Input (Joules /in.)	Penetration %	Remark
SA-6	BOP	130	6	Sharp	0.040	30	10	R-40	1560	100	Top concavity
SA-7	BOP	130	5	Sharp	0.040	30	10	R-40	1300	100	Good
SA-8	Butt	130	6	Sharp	0.040	30	10	R-40	1560	100	Good - more drop through
SA-9	Butt	130	5	Sharp	0.040	30	10	R-40	1300	100	Good - less drop through
Samples	Butt	130	5	Sharp	0.040	30	10	R-40	1300	100	Good
Tensile Test Specimens	Butt	130	4.3	Sharp	0.040	30	10	R-40	1118	100	Good

* SA - Solution Annealed - Before Welding
* A - Solution Annealed and Aged - Before Welding
** BOP - Bead on Plate
** Butt - Square Butt Joint

TABLE 8
EB WELD PROCESS PARAMETERS - Ti-15V-3Cr-3Al-3Sn
0.300-IN. THICK MATERIAL

Sample No.*	Type of Weld**	kV	mA	Focus	Circle Generator dia. (in.)	Weld Speed (ipm)	Work Dist. (in.)	Heat Input (Joules /in.)	Penetration %	Remarks
SA-10	Butt	130	12	0.020	None	30	6	3120	75	Top satisfactory - incomplete penetration
SA-11	Butt	130	14	0.020	None	30	6	3640	80	Top satisfactory - incomplete penetration
SA-12	BOP	140	15	0.020	None	30	6	4200	100	Top undercut
SA-13	BOP	140	12	0.020	None	30	6	3360	80	Top satisfactory - incomplete penetration
SA-14	BOP	140	14	0.020	None	30	6	3920	100	Satisfactory visual appearance
SA-15	Butt	140	14	0.020	None	30	6	3920	100	Top undercut - excessive drop through
SA-16	Butt	140	14	0.030	None	30	6	3920	100	Top undercut - penetration complete
SA-17	Butt	140	13	0.030	None	30	6	3640	100	Slight undercut penetration complete
SA-18	Butt	140	13	0.030	None	30	6	3640	100	Slight undercut penetration complete
	Cosmetic	140	4		0.080	30	6	1120		
SA-19	Butt	140	12	0.030	None	30	6	3360	100	Top satisfactory - penetration complete
	Cosmetic	140	4		0.080	30	6	1120		

SA-19 parameters were used for test panels
* - SA - Solution Annealed - Before Welding
** - BOP - Bead On Plate
** - Butt - Square Butt Joint

found no anomalies in welding this alloy. The test results, both as-welded and in the aged condition, will be discussed in other sections of this report. The non-destructive testing, X-ray and dye penetrant testing of all welded samples indicated that all samples met the weld criteria established for this program. There were no cracks and the amount of pores found were few and extremely small, in the 0.001- to 0.003-inch size category. Of all panels tested there was one 0.015-inch pore and one 0.012-inch pore. These would pass inspection standards for material 0.100 inch and thicker.

2. GAS-TUNGSTEN ARC WELDING

GTA weld variables investigated during the program were those affecting heat input, so attention was focused on current, voltage and travel speed. Pre-heat and post-heat treatments were considered but no weld cracking problems were encountered so these methods were not investigated. A straight butt joint for the fusion welds without filler wire and a 60° included angle "V" joint for filler wire welds was used. These two joint configurations worked very well. The Air-Line, flat-stock weld fixture worked very well and the gas (argon) coverage on the underside of the weld bead was adequate, giving a clean weld bead in all cases. Argon troch gas was used along with a Bell-developed trailing shield of argon gas. This protected the top side of the weld bead, which was also very clean.

a. Task II - 0.050-Inch Thick Welding

Initial weld parameters were investigated on Ti-6Al-4V sheet to conserve material. This also gave a good comparison as to the weldability of the Ti-15V-3Cr-3Al-3Sn alloy. Table 9 shows the GTA parameters used for welding and also parameters used for welding the tensile and bend test specimens. All test panels were non-destructively tested by X-ray and dye penetrant methods. There were no cracks and the limited porosity found was well below the commonly specified maximum diameter of 25% of joint thickness. Mechanical properties and metallurgical examinations of these test panels will be discussed in other sections of this report. Figure 4 shows a typical GTA weld in 0.050-inch thick sheet.

TABLE 9
GTA WELD PROCESS PARAMETERS - Ti-15V-3Cr-3Al-3Sn

Gas Tungsten Arc - 0.050 in. Thick Material
Equipment - P&H Power Supply
Heliweld Automatic Weld Head
Linde Machine Carriage
Air Line Welding Positioner

Sample Number	Type of Joint	Current (amps)	Volts	Weld Speed (ipm)	Torch Gas (cfh)	Back up Gas (cfh)	Trailer Gas (cfh)	Remark
1	0.062 in. Butt 6Al-4V	74	6.5	13.0	20	25	10	Preliminary settings
2	0.050 in. Butt	70	6.25	12.5	20	25	10	Marginal penetration
3	0.050 in. Butt	72	6.5	11.0	20	25	10	Increase in penetration
4	0.050 in. Butt	71	6.75	11.0	20	25	10	Good weld. These parameters used on samples.

Butt - Square butt joint
cfh - Cubic feet per hour

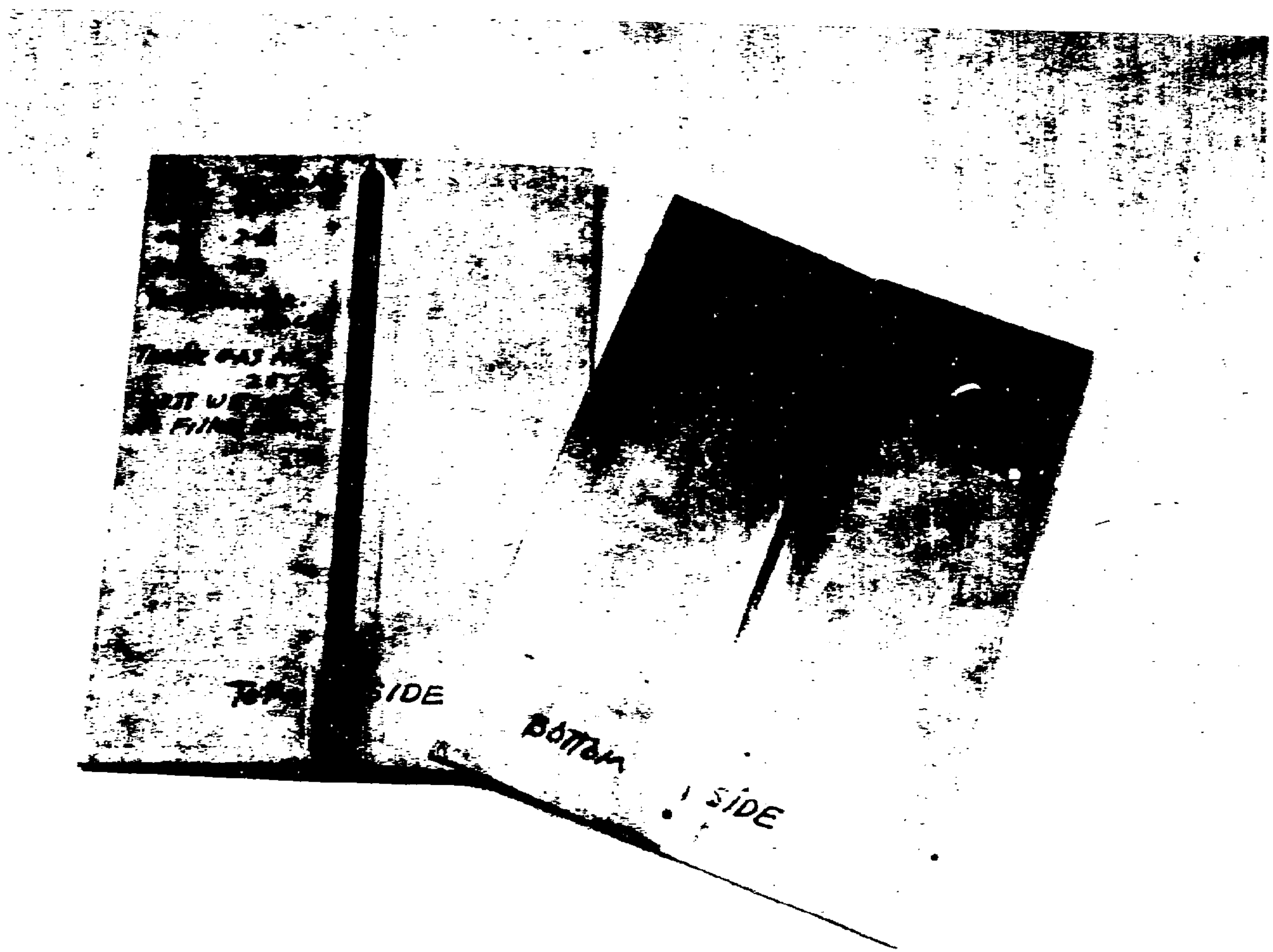


Figure 4. Gas Tungsten Arc (GTA) Weld Sample

b. Task III - 0.100-Inch Thick Welding

Welding of the 0.100-inch thick material was carried out in the same manner as the 0.050-inch thick material. Initial parameters were on Ti-6Al-4V and then butt welds of Ti-15V-3Cr-3Al-3Sn were set up and welded. Table 10 shows the parameters used and the GTA weld parameters used for the tensile and bend test samples. There were no anomalies in welding this material and X-ray and dye penetrant tests indicated the weldments were crack-free and well within the specified porosity limits. Mechanical properties and metallurgical examinations of these weldments will be discussed in other sections of this report.

TABLE 10
GTA WELD PROCESS PARAMETERS - Ti-15V-3Cr-3Al-3Sn

Gas Tungsten Arc - 0.100 in. Thick Material

Equipment - P & H Power Supply
Hellweld Automatic Weld Head
Linde Machine Carriage
Air Line Welding Positioner

Sample Number	Type of Joint	Current (amps)	Volts	Weld Speed (ipm)	Torch Gas (cfh)	Back up Gas (cfh)	Trailer Gas (cfh)	Remark
5	0.100 Butt	96	8.5	4	20	25	10	Poor penetration
6	0.100 Butt	100	8.5	5	20	25	10	Good weld
7	0.100 Butt	135	6.5	6	20	25	10	Good weld - less penetration
Samples tensile test	0.100 Butt	135	6.5	5.5	20	25	10	Good welds

Butt - Square butt joint
cfh - Cubic feet per hour

It was part of this program to GTA weld the 0.100-inch thick material with filler wire in addition to GTA and EB welds without filler wire. Ti-15V-3Cr-3Al-3Sn filler wire was furnished by AFML. It was centerless ground, 1/16-inch diameter wire. The sheet material was prepared for welding by machining a "V" groove configuration. The "V" groove was a 60° included angle with an 0.020-inch land on the bottom side. This weld joint configuration is extensively used in industry and direct comparisons can be made to this alloy's weldability versus Ti-6Al-4V. The equipment used for welding is the same equipment used to butt-weld the 0.050- and 0.100-inch thick material with the GTA process. A wire feeder was used to feed straight lengths of wire automatically into the weld puddle. The description of equipment and weld parameters developed is given in Table 11.

Three sets of test panels were welded. There were no anomalies in the welding of this material with wire. The material is considered to have good weldability under these conditions.

Three sets of sample weldments were non-destructively tested by X-ray and dye penetrant. There was scattered porosity, but the pores were very small and well within a diameter maximum of 25% of joint thickness. There were no cracks found in any of the weldments. Three sets of sample weldments were tensile and bend tested in the following material conditions: as-welded and aged for eight hours at 900 and 950°F. These samples were metallurgically examined and a hardness traverse was made. Mechanical and metallurgical properties will be reported in other sections of this report.

TABLE 11
GTA WELD PROCESS PARAMETERS Ti-15V-3Cr-3Al-3Sn WITH FILLER WIRE

Gas Tungsten Arc - 0.100 in. Thick Material

Equipment - P&H Power Supply
Heliweld Automatic Weld Head
Linde Machine Carriage
Air Line Welding Positioner
Linde Wire Feed

Sample Number	Type of Joint	Current (amps)	Volts	Weld Speed (ipm)	Wire Feed ipm	Torch Gas (cfh)	Back up Gas (cfh)	Trailer Gas (cfh)	Remark
8	0.100 "V" -groove	95	8.5	4	12	20	25	10	Lack of penetration
9	0.100 "V" -groove	140	8.0	5	12	20	25	10	Lack of penetration
10	0.100 "V" -groove	170	8.0	6	12	20	25	10	Good weld
Samples tensile test	0.100 "V" -groove	170	8.0	5.5	12	20	25	10	Good welds

Joint Preparation - 60° included angle with 0.020 in. Land - "V" Groove
cfh - Cubic feet per hour

SECTION IV

HEAT TREATMENT OF Ti-15V-3Cr-3Al-3Sn

The response to heat treatment of the Ti-15V-3Cr-3Al-3Sn alloy will be reviewed as a preface to describing the weld microstructure. This alloy contains a large proportion of beta stabilizers; consequently, the beta structure, produced by heating above about 1400°F, is retained when the material is cooled, even at slow rates, to room temperature. The resulting metastable beta body-centered cubic phase in very ductile but of moderate strength. Upon reheating during aging (900 - 1100°F), some of the beta phase is transformed by precipitation of a finely dispersed hexagonal close-packed alpha phase with an accompanying increase in strength and lowering of ductility.

Specimens examined were in the solution annealed condition before welding. Welding exposes part of the joint, near the weld, to temperatures up to the melting point, around 3000°F. All areas heated above 1400°F would receive a second solution anneal. Upon subsequent aging, all zones, having had either one or two solution anneals, would transform to the aged or alpha/beta structure.

Data are presented in the form of photomicrographs (Figures 5 - 10) and hardness plots (Figures 12-17) of GTA and EB welds in three gages of solution annealed material which were aged 950°F, four hours, after welding. Hardness surveys are shown for the above joints, as well as for one as-welded joint in aged 0.050-inch sheet.

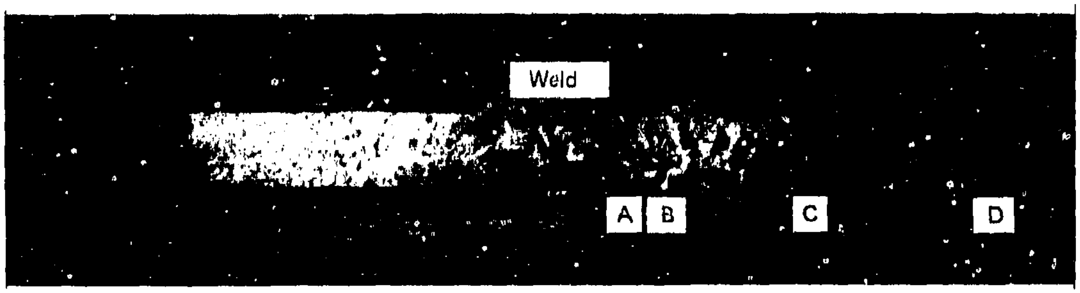
The top photograph in Figures 5-10 shows the welded joint at 10X magnification, and serves as a key to the location of the 50X and 100X photomicrographs of the several zones. The 10X view shows the size of the weld and the light-etching heat-affected zone (HAZ). Both weld and HAZ are narrower in the EB welded joint than in their GTA counterparts, the reason being the lower heat input of the EB process.

The 50X view of the edge of the weld shows the fusion line (marked by arrows) with enough of the weld included to show the large columnar grains of the weld. The grain size is somewhat smaller in the EB specimens. Immediately outside the fusion line are several rows of grains of recrystallized base metal, enlarged and equiaxed in shape. In the EB specimen these are about half the diameter of those in the GTA specimen.

The welds in this program consistently have fractures with a coarse pattern. In view of the tendency for the alpha phase to precipitate in grain boundaries, it was thought that the fractures were of an intergranular type, that is, fracture taking place along the relatively weaker alpha layer in the boundaries. However, it appears that this is not true.

In order to learn more about the fracture mode, a GTA-welded longitudinal tensile bar which had been aged at 900°F was reassembled and sectioned lengthwise. This section is shown in Figure 11. The fracture was found to be over 90 percent of a transgranular cleavage mode rather than intergranular. This transgranular cleavage probably followed cleavage planes in the large grains or dendrites of the weld metal. Two shorter ruptures are visible in Figure 11 at the right side of the picture. Each of these lies about half in a boundary and half within the grain.

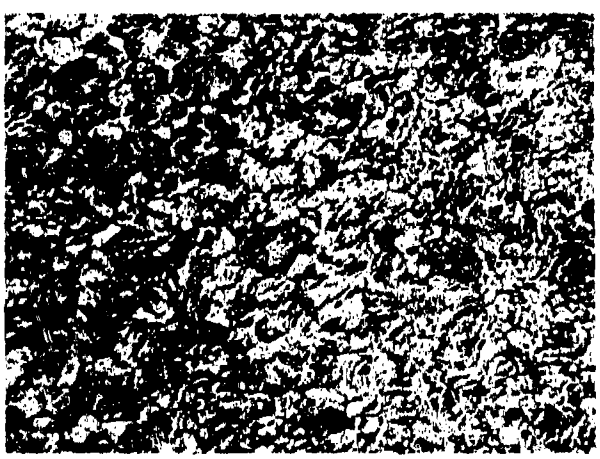
It is noteworthy that most weld specimens welded and aged at 950°F for four hours failed 0.4-0.5 inch from the edge of the weld. This put the failure site well beyond the heat-affected zone.



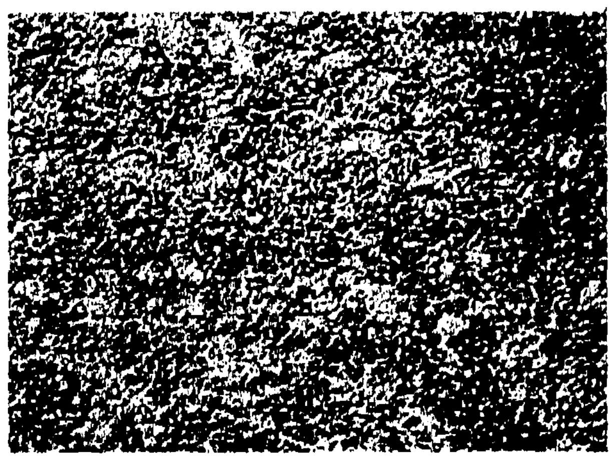
Section Across GTA Weld No. 26, Showing Location of Photomicrographs. 10X

A. Edge of Weld (arrows). 50X

B. Edge of Weld (arrows). 100X

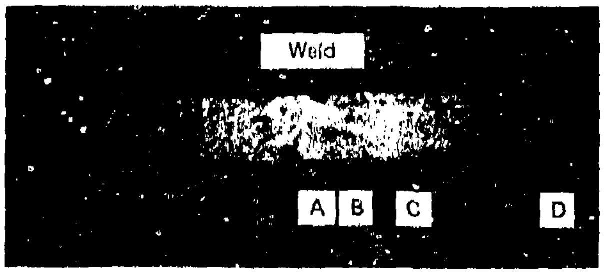


C. Heat-affected Zone. 100X



D. Unaffected Base Metal. 100X

Figure 5. Microstructure of Gas Tungsten Arc Weld in 0.050-Inch Annealed Sheet, Aged After Welding, 950°F-4 Hr. Ti-15V-3Cr-3Al-3Sn



Section Across EB Weld No. 22, Showing Location of Photomicrographs. 10X

A. Edge of Weld (arrows). 50X

B. Edge of Weld (arrows). 100X

C. Heat-affected Zone. 100X

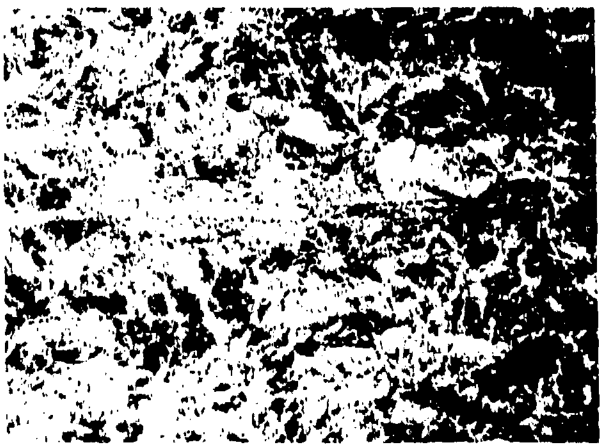
D. Unaffected Base Metal. 100X

Figure 6. Microstructure of Electron Beam Weld in 0.050-Inch Annealed Sheet, Aged After Welding, 950°F-4 Hr, Ti-15V-3Cr-3Al-3Sn

Section Across GTA Weld No. 36 in 0.100-inch Sheet. Solution Annealed Sheet, Welded, Then Aged 950°F. Letters Show Location of Photomicrographs. 10X

A. Edge of Weld (arrows). 50X

B. Heat-affected Zone. 50X

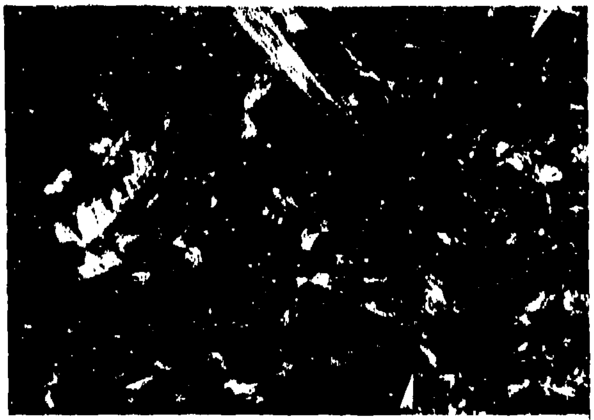


B. Heat-affected Zone. 100X

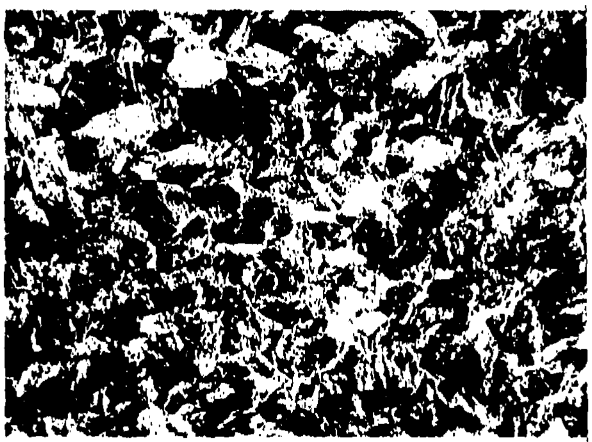
C. Unaffected Base Metal. 100X

Figure 7. Microstructure of Gas-Tungsten Arc Weld in 0.100-Inch Solution Annealed Sheet, Aged After Welding, 950°F-4 Hr

Section Across EB Weld No. 41. Solution Annealed Sheet, Welded, Then Aged 950°F-4 Hr. 10X



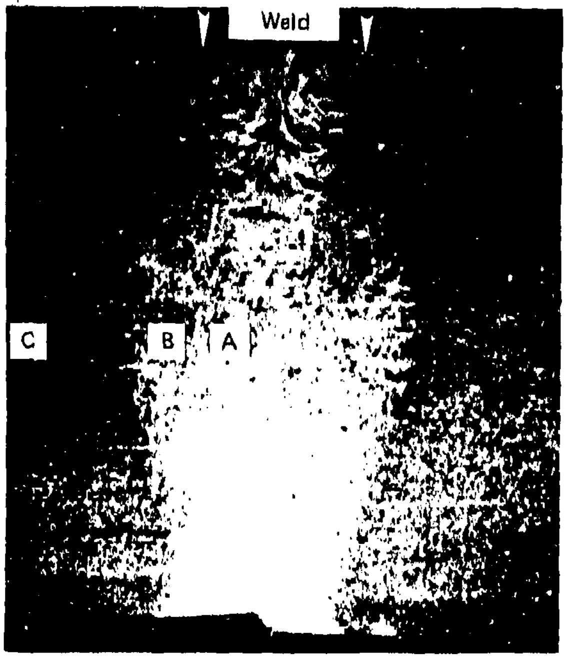
A. Weld lies left of arrows, and part of heat-affected zone is to right. 50X



B. Heat-affected Zone. 100X

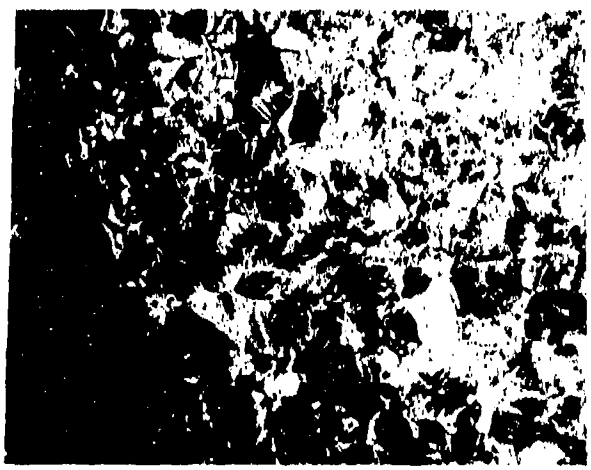
C. Unaffected Base Metal. 100X

Figure 8. Microstructure of Electron Beam Weld in 0.100-Inch Solution Annealed Sheet, Aged After Welding, 950°F-4 Hr



Section across EB Weld No. 66 in 0.300-inch plate. Aged after welding. This shows location of photomicrographs. 10X

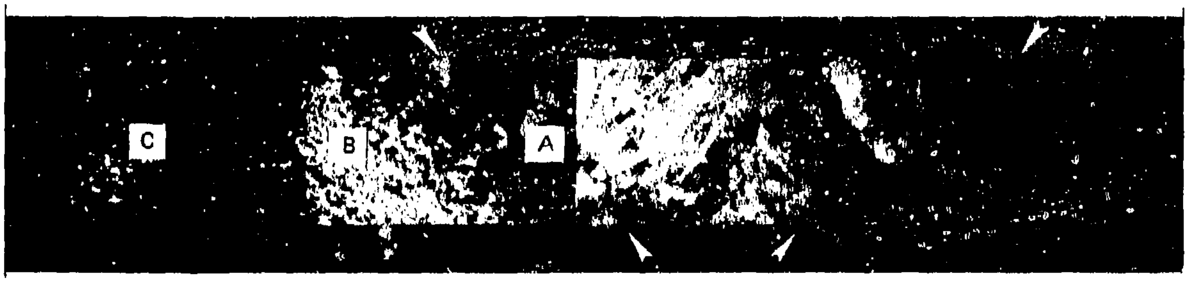
A. Weld (to right of arrows) and part of heat-affected zone to left. 50X



B. Heat-affected Zone. 100X

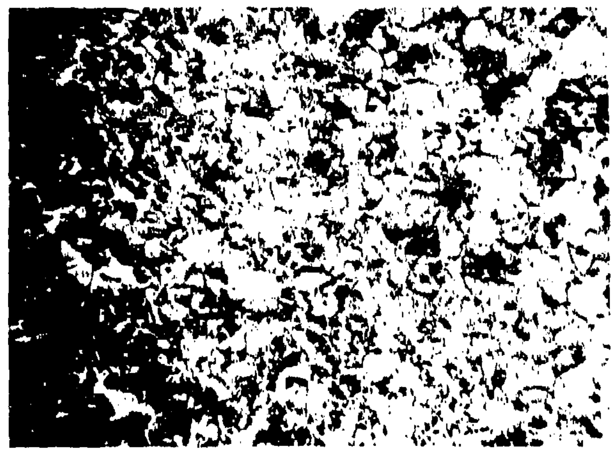
C. Unaffected Base Metal. 100X

Figure 9. Microstructure of Electron Beam Weld in 0.300-Inch Solution Annealed Plate, Aged After Welding, 950°F-8 Hr



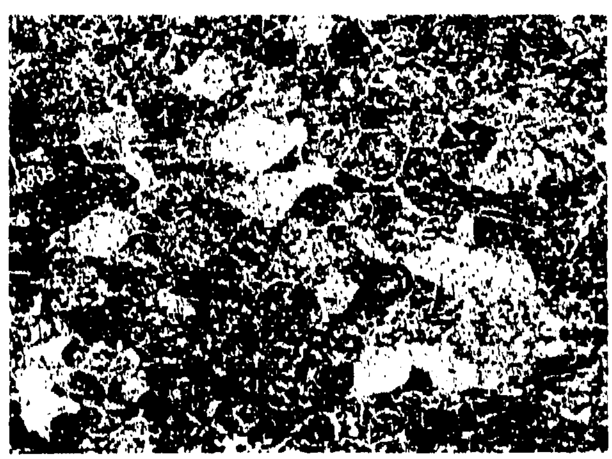
Section across GTA Weld No. 79-1. Reinforcement has been removed.
Letters show location of photomicrographs. 10X

A. Edge of Weld (arrows). 50X



B. Heat-affected Zone. 50X

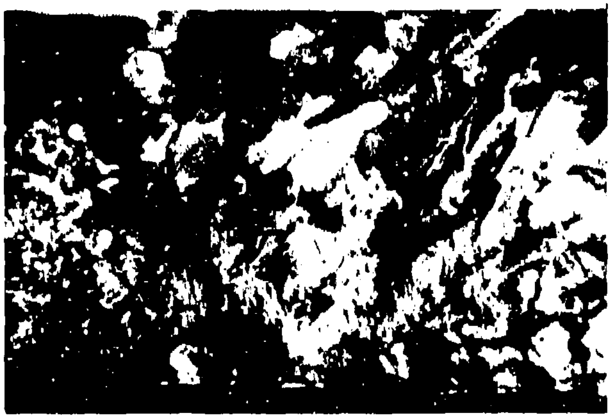
B. Heat-affected Zone. 100X



C. Unaffected Base Metal. 100X

Figure 10. Microstructure of Gas-Tungsten Arc Weld With Filler Wire in 0.100-Inch Solution Annealed Sheet, Aged After Welding, 950°F-8 Hr. Heat P2360, Ti-15V-3Cr-3Al-3Sn

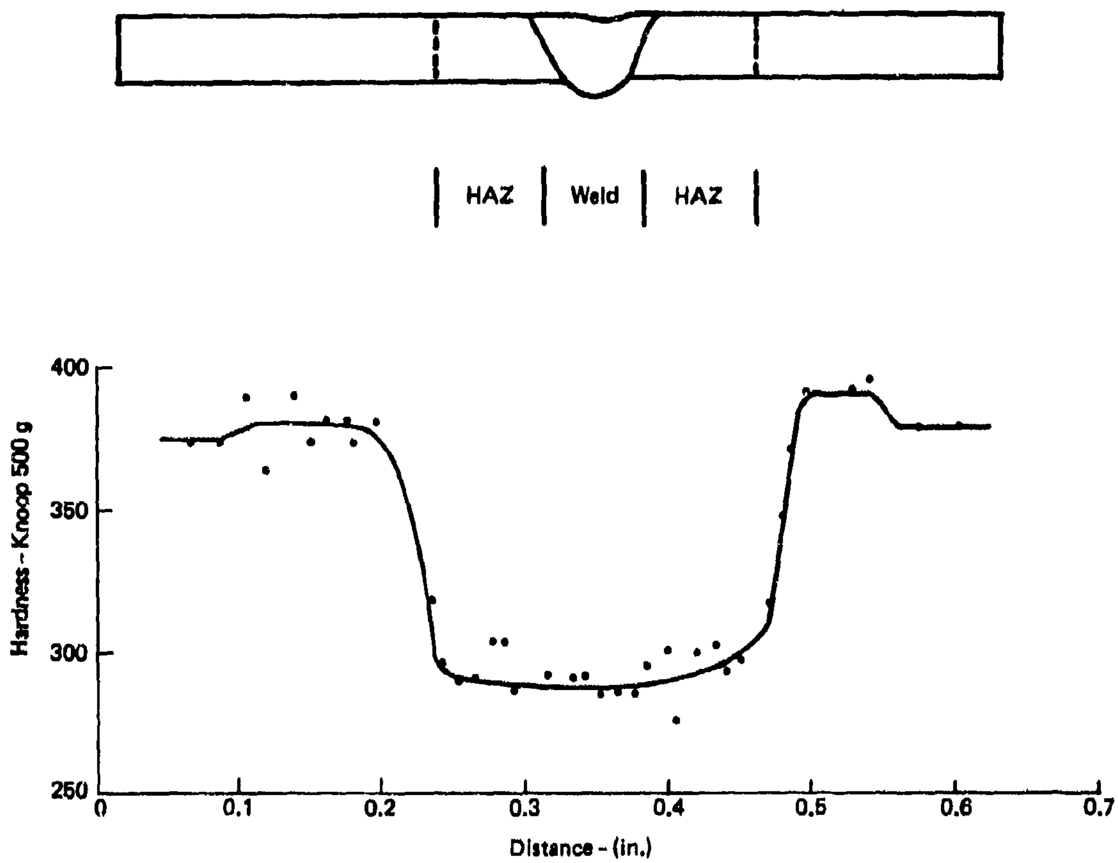
Fracture face of a bend test specimen. The weld (arrows) is perpendicular to the plane of the paper. 6X



Detail of above weld face showing flat facets developed by cleavage fracture within the coarse grains of weld metal. 25X

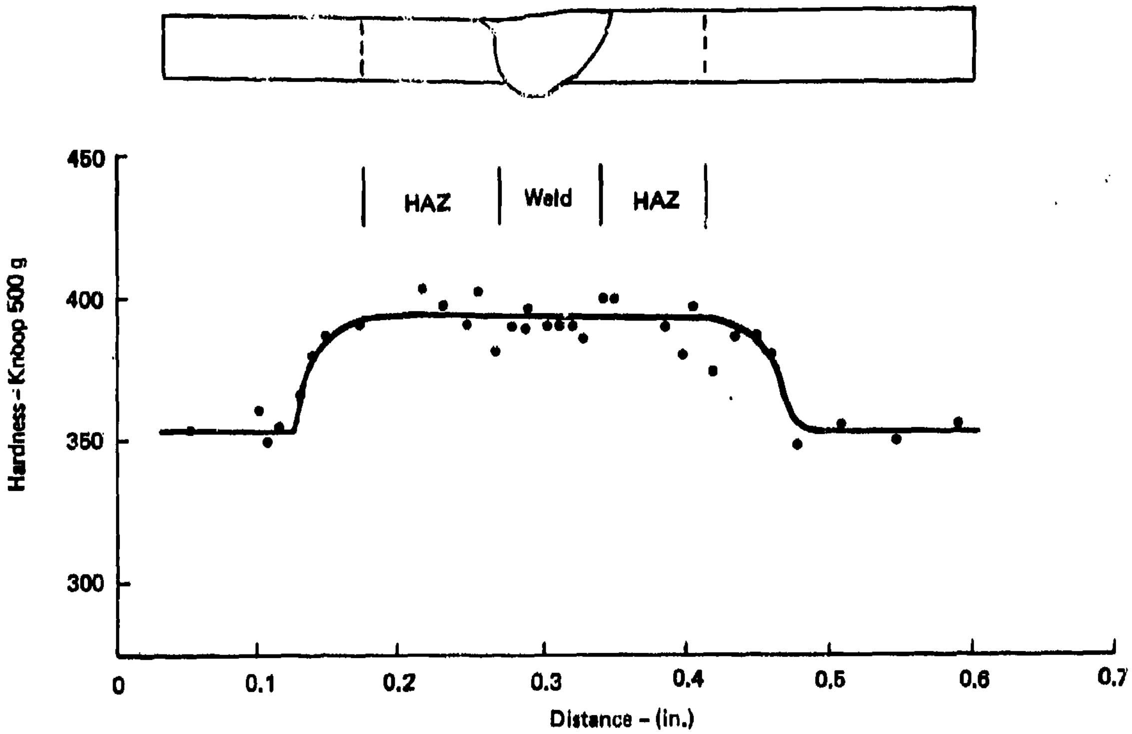
Longitudinal tensile bar sectioned lengthwise of bar and perpendicular to surface. Fracture is 90% through grains, not through boundaries. 25X

Figure 11. Fracture Pattern in GTA Welds Aged at 900°F



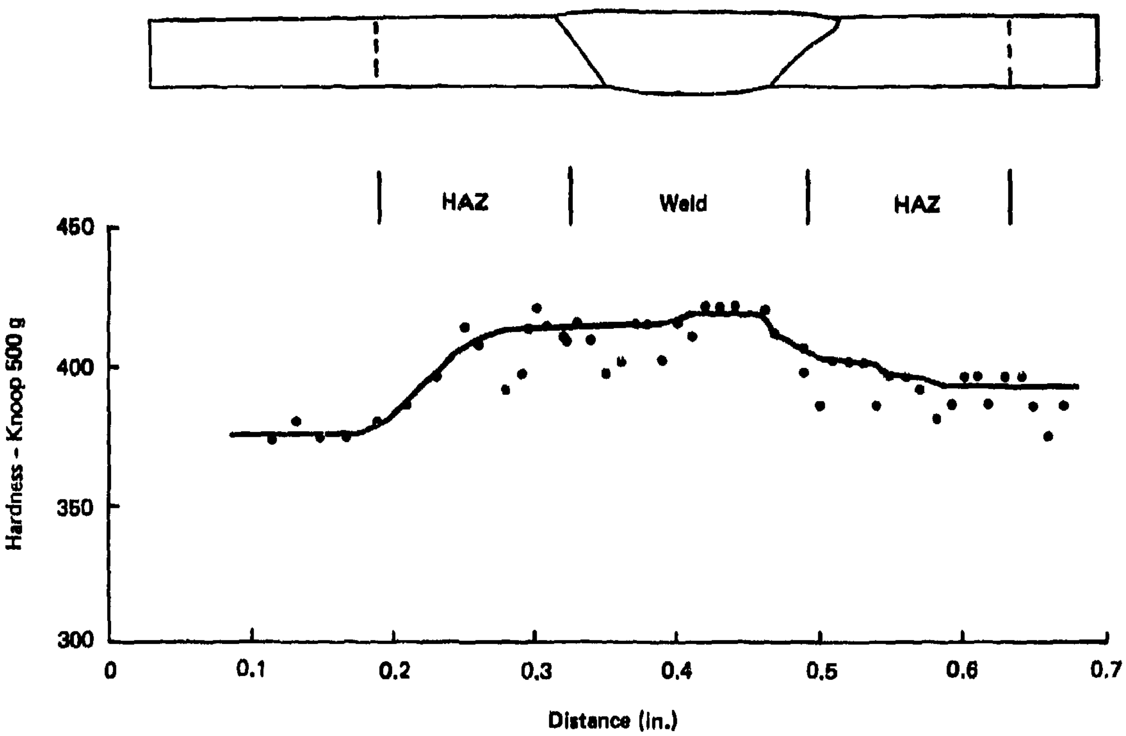
Material = 0.050 - Inch Ti-15V-3Cr-3Al-3Sn
Weld = Electron Beam
Heat Treat = Aged Sheet (950°F) In As-Welded Condition

Figure 12. Hardness Survey, As-Welded EB Weld in 0.050-Inch Aged Sheet (Welded after Aging)



Material	= 0.050 – Inch Ti-15V-3Cr-3Al-3Sn
Weld	= Electron Beam
Heat Treat	= Annealed Sheet, Weld, Age 950°F-4 hr

Figure 13. Hardness Survey, EB Weld in 0.050 Inch, Aged 950°F



Material	=	0.050 Inch Ti-15V-3Cr-3Al-3Sn
Weld	=	Gas Tungsten Arc
Heat Treat	=	Annealed Sheet, Weld, Age 950°F-4 hr

Figure 14. Hardness Survey, GTA Weld in 0.050 Inch, Aged 950°F

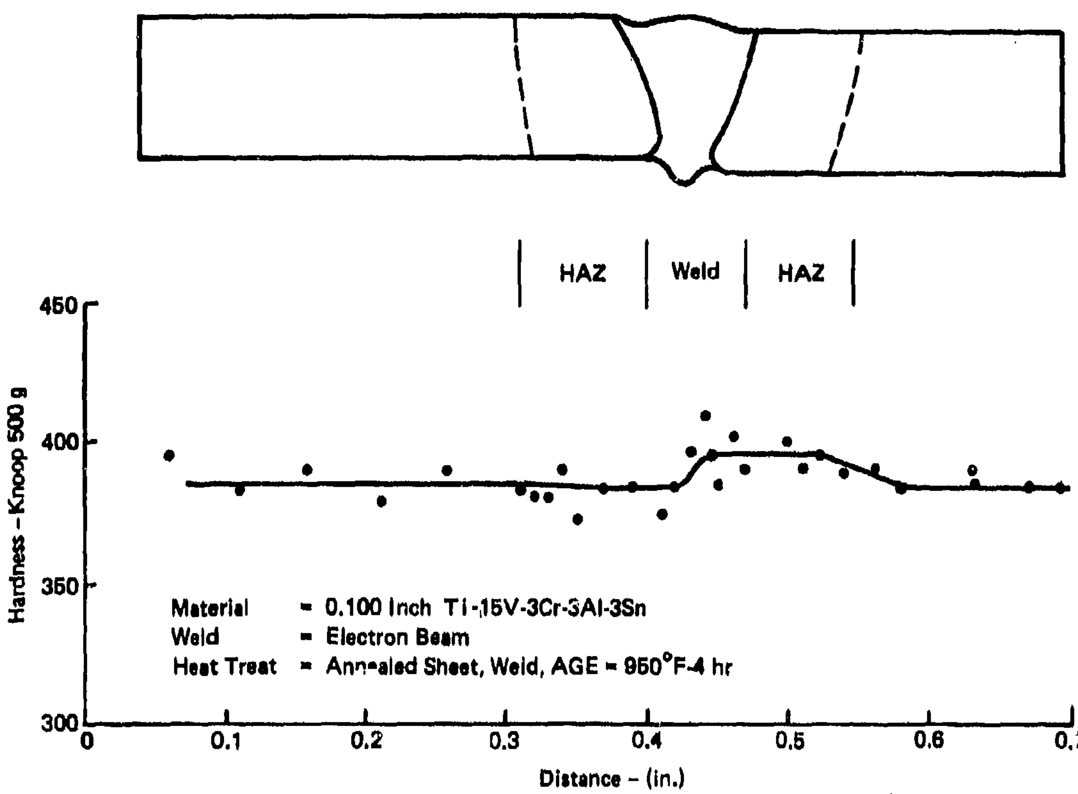
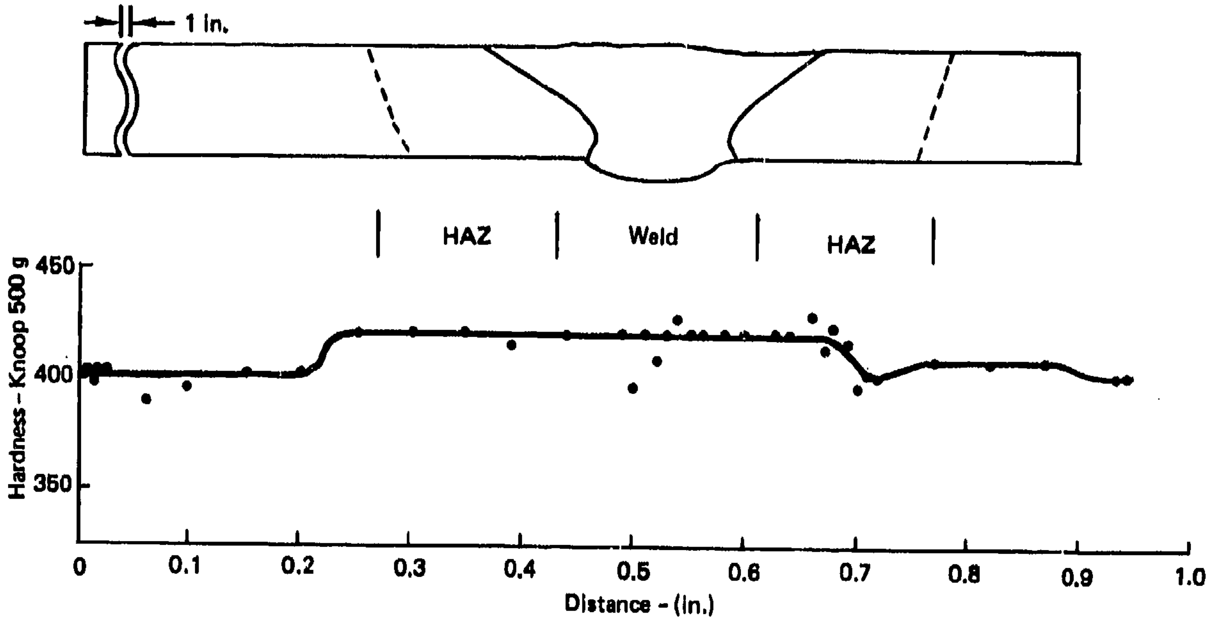
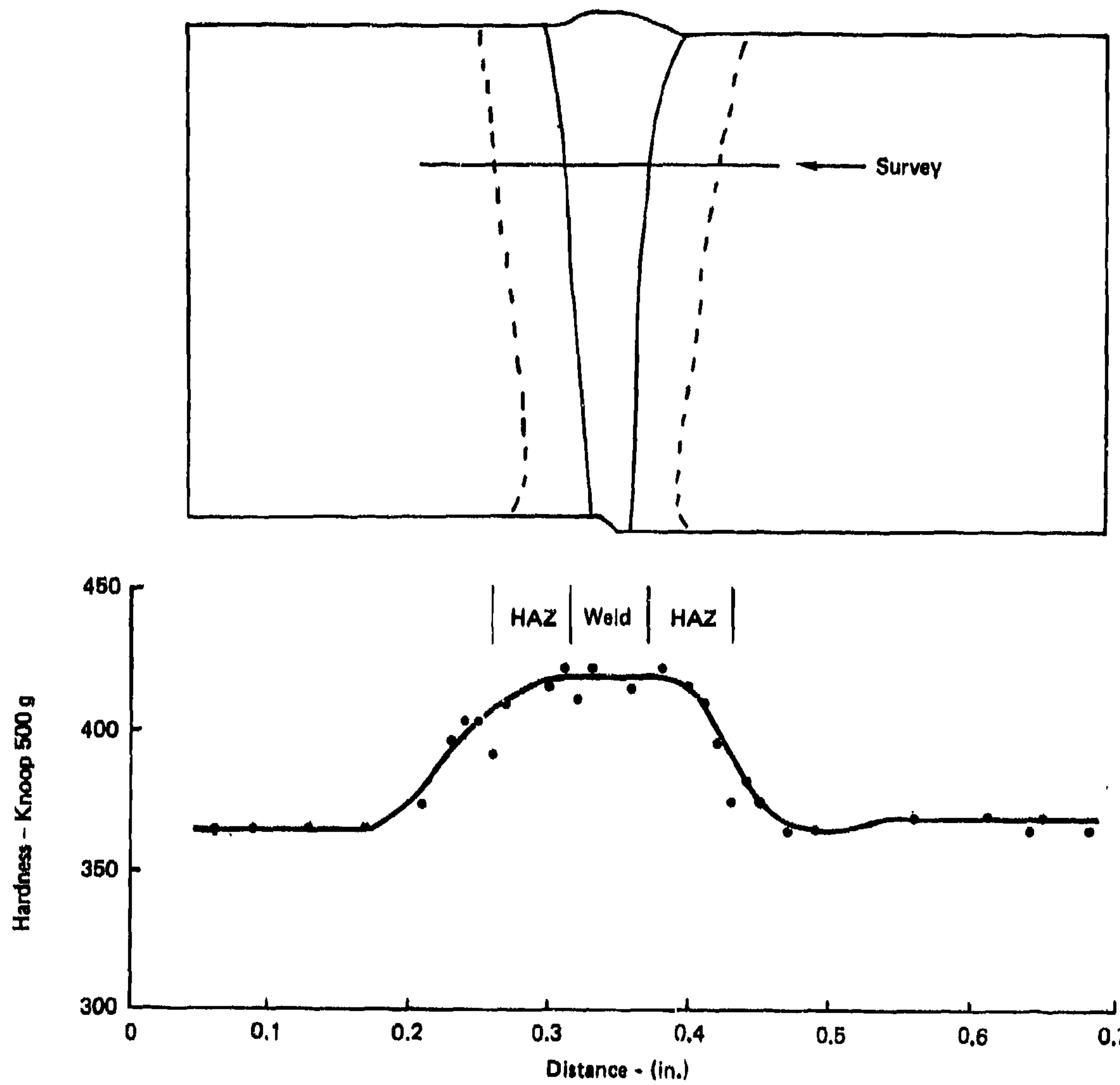


Figure 15. Hardness Survey, EB Weld in 0.100 Inch, Aged 950°F



Gage	=	0.100 - Inch Ti-15V-3Cr-3Al-3Sn
Weld	=	Gas Tungsten Arc
Heat Treatment	=	Annealed Sheet, Weld, Age 950°F-4 hr

Figure 16. Hardness Survey, GTA Weld in 0.100 - Inch, Aged at 950°F



Material	=	0.300-Inch Ti-15V-3Cr-3Al-3Sn
Weld	=	Electron Beam
Heat Treat	=	Annealed Sheet, Weld, Age 950°F-8 hr

Figure 17. Hardness Survey, EB Weld in 0.300-Inch, Aged 950°F

The bulk of the heat-affected zone, shown by 100X photomicrographs, shows no noticeable difference between GTA and EB specimens. Here, as in the fusion zone, the structure is lightened in color by alpha precipitate.

The base metal beyond the HAZ has the structure typical for the aged alloy, being a finely dispersed alpha/beta mixture. All samples in 0.100- and 0.300-inch thickness show some strings of elongated grains, possibly un-recrystallized material.

The hardness surveys of the welded-and-aged joints reveal that there were no soft zones; in fact, the opposite was true in that the weld and HAZ zones were somewhat harder than the base metal remote from the joint. This elevation of hardness, amounting to 10 to 50 points on the Knoop 500-gm scale, is an indication that the weld and HAZ are stronger, but at the same time less ductile, than the base metal. The bend ductility of the welded joints also is about half as good as the base metal.

The first hardness plot (Figure 12) is important because it shows an as-welded joint in aged sheet. It is indicative of the hardness of the weld and HAZ of the other specimens before their post-weld aging. Because of the welding heat, the weld and the HAZ have been returned to the soft beta phase condition. The hardness is a uniform Knoop 290, and the tensile strength of test bars was around 125,000 psi with fracture occurring in the weld. Longitudinal welded tensile specimens of this type had 10 percent elongation, approximately the same as aged base metal.

The hardness surveys of the welded-and-aged specimens consistently show an elevation of hardness in the weld and HAZ; moreover, it was about the same across those two regions. There were no detectable drops in hardness in the HAZ from overaging. This might have occurred where the exposure temperature in the HAZ was around 1200°F. Doubtless, the short time at temperature during welding avoided overaging.

Not all of the hardness plots are symmetrical on both sides of the weld. This is attributed to variability in the heat sink characteristics of the weld fixture. Figure 16 is particularly off-center. This is not a data plotting error because the hardness indentation location was carefully referenced to features on the specimen.

Not all specimens show the same elevation in hardness in the weld - HAZ plateau. This is not related to the welding process but rather is a function of the heat-treat response of the particular gage of sheet. For example, both EB and GTA welds in 0.050-inch gage show an elevation of 40 Knoop points. In 0.100-inch gage the elevation is 10 and 20 points for EB and GTA, respectively. The elevation of the EB weld in 0.300-inch gage is 50 Knoop points.

SECTION V

MECHANICAL PROPERTIES

Mechanical property tests conducted in establishing weld processes were the bend test and the tensile test. These two tests will be discussed with comments on the individual material thicknesses and heat treat conditions.

In titanium alloy sheet welds, ductility is probably the most important measure of weld quality, especially as a sensitive indicator of contamination during welding. Ductility is most easily determined by a bend test. In this test, the weld can be oriented either transverse (weld parallel to bend axis) or longitudinal (weld perpendicular to bend axis), with respect to the length of the strip being bent. Transverse bend tests are the type most commonly used and they serve to reveal fusion defects oriented lengthwise of the weld. However, when zones of varying strength are present there is a problem of uneven straining, with most of the bending occurring in the softer zones. Some preliminary transverse bends with the subject pieces showed the weld beads to be relatively soft so that most of the bending occurred there. In order to get a more uniform bend, longitudinal samples were used. These strain all parts of the joint equally so that hard or brittle zones are revealed by their low ductility.

Bend specimens were 1 x 4 inches in size with the weld running lengthwise, except that those of EB welds in annealed sheet were 0.5 x 4 inches. The EB weld melt-thru was ground flush, but the top was flat and was not ground. GTA welds were almost flat, so most were not ground.

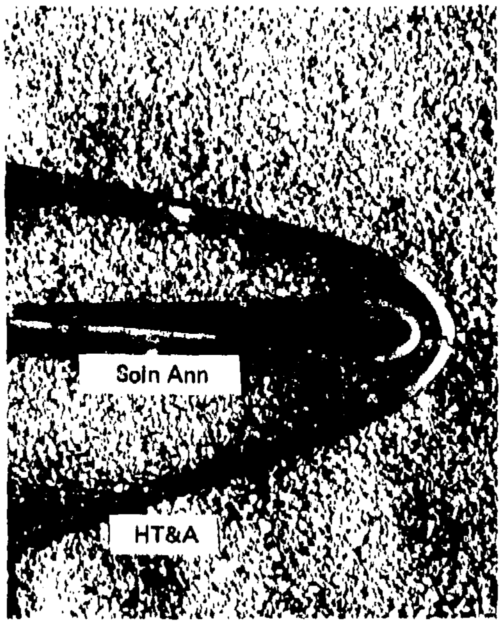
Free-bend tests were used. The bend was initiated with a prebend over a one-inch diameter mandrel to an included angle of 160°. The piece was end-loaded in a vise to further deform it. At intervals, the bend radius was measured on the inside while the tension side was examined for cracks with a 10X hand lens.

The bend radius was measured by comparison to a set of rods graduated in 1/32-inch intervals, and in smaller sizes, in 1/64-inch intervals. The rod was placed in the bend and illuminated from the far side. This gave a silhouette which permitted a precise comparison.

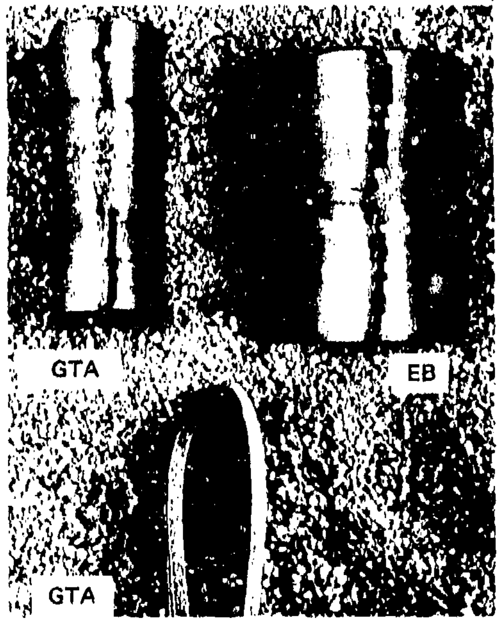
Tensile specimens were standard ASTM type E8 sheet specimens having a reduced section 0.5-inch wide by 2.25-inch long. Specimens were in triplicate for welded pieces and in duplicate for base metal tests. Welds were oriented across the specimen for transverse weld tests and lengthwise for longitudinal weld tests.

1. TASK II - 0.050-INCH THICK MATERIAL-MECHANICAL PROPERTIES

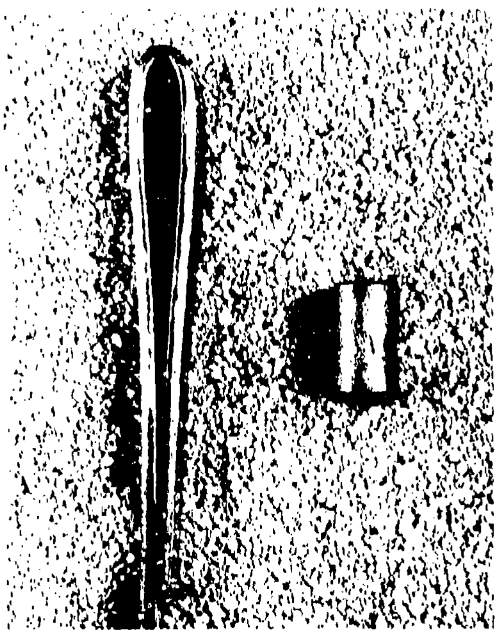
Specimens after bending are shown in Figure 18. Bend and tensile test results are given in Table 12. Bending response was more like that of stainless steel than like the customary alloys such as Ti-6Al-4V. Lower spring-back than for the Ti-6Al-4V alloy was noticeable in aged sheet and was a prominent feature of annealed sheet.



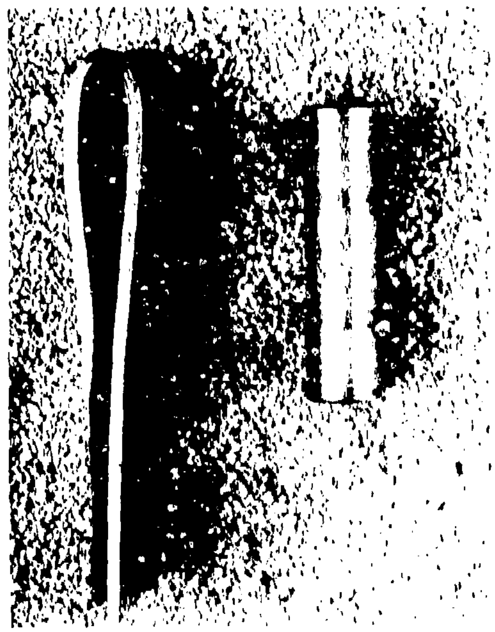
Unwelded Base Metal



Welds in Solution Heat-Treated and Aged Sheet.



EB Welds in Annealed Sheet.



GTA Welds in Annealed Sheet.
Mag: 1.6X

Figure 18. Free-Bend Tests of Base Metal and As-Welded Welds In 0.050-in. Gage Ti-15V-3Cr-3Al-3Sn Sheet

TABLE 12
MECHANICAL PROPERTIES
0.050 Inch Thick Material

Heat No.	Gage (in.)	Condition	Rolling and Weld Direction	Ult. Strength ksi	Ult. Strength MPa	Yield Strength ksi	Yield Strength MPa	Elongation% 2 in. or 50 mm	Longitudinal Bend (XT) Pass	Longitudinal Bend (XT) Fail
V5031	0.050	SA & EB Weld	L	118	813	105	723	12	0.7	
			L	116	799	106	730	13		
			L	116	799	104	717	14		
			T	117	806	111	765	12		
			T	117	806	112	772	11		
			T	117	806	113	779	10		
		SA + Age 950°F 4 hr + EB Weld	L	149	1027	133	916	11	1.2	
			L	148	1020	132	909	11		
			L	153	1054	132	909	11		
			T	125	861	121	834	3		
			T	128	882	123	848	3		
			T	126	868	122	841	4		
		SA + GTA Weld	L	117	806	100	689	13	0.9	
			L	119	820	98	675	14		
			L	118	813	101	696	14		
			T	115	792	109	750	8		
			T	115	792	109	750	10		
			T	116	799	110	757	10		
		SA + Age - 950°F 4 hr + GTA Weld	L	130	896	114	786	9	0.9	
			L	129	889	112	772	9		
			L	132	923	113	779	10		
			T	124	854	118	813	6		
			T	123	847	117	806	6		
			T	124	854	117	806	6		
		SA + EB Weld + Age - 950°F - 4 hr	L	165	1137	154	1061	10	10	9
			L	161	1109	-		10	6.3	5
			L	170	1171	162	1116	10		
			T	177	1220	171	1178	8		
			T	180	1240	172	1186	7		
			T	163	1223	154	1061	9		
		SA - GTA Weld + Age - 950°F - 4 hr	L	164	1130	159	1096	7	-	10
			L	163	1123	158	1089	8	-	10
			L	174	1199	168	1158	2.5*		
			T	161	1109	153	1054	6		
			T	161	1109	153	1054	5		
			T	161	1109	151	1040	3*		

* - Broke outside gage marks.

The following conditions of material were used in the original test program:

Material to be welded -

1) Solution anneal (at supplier)
2) Solution anneal (at supplier), aged at Bell 950°F, 4 hr

Tests were made on specimens in the as-welded condition. These as-welded specimens were highly ductile, all remaining sound at less than one T bend radius (T being the thickness of the sheet). Solution annealed sheet was also very ductile, passing bend tests of less than one T. Welds made in solution annealed and aged sheet produced an annealed zone on each side of the weld extending

0.050 - 0.070 inch. This zone and the weld were ductile. Unaffected base metal beyond this zone was less ductile, having bend properties normal for aged based metal. Photographs of the welds in the previously aged sheet show the base metal crack and that the crack stopped at the ductile heat affected zone and weld.

Photographs of typical broken specimens are shown in Figure 19. These welds were in the as-welded condition and they had a strength nearly the same as the solution annealed base metal. This was to be expected since the welds in cooling developed an all-beta microstructure similar to that of the solution annealed plate. Failure was in the weld metal in all the transverse specimens except for EB welds in annealed sheet, these breaking about 0.25 inch from the weld.

Longitudinal welds in aged sheet were stronger than those in annealed sheet because the 0.5-inch specimen width encompasses 0.1 - 0.2 inch of unaffected metal beyond the heat affected zone. Thus, the GTA weld in aged sheet was 10 percent stronger than a GTA weld in annealed sheet, and the EB weld, with its narrow heat-affected zone, was 33 percent stronger.

Bend and tensile tests were also conducted in weldments of 0.050-inch sheet in the following condition:

1) Solution annealed (at supplier) - GTA welded - aged at 950°F for four hours.
2) Solution annealed (at supplier) - EB welded - aged at 950°F for four hours.

Bend tests in these aged weldments had a bend radius approximately double (i.e., half as good) that of aged base metal. These bend results were somewhat poorer than expected, in view of the unusually high ductility of the as-welded joints. It was anticipated that a radius closer to base metal results would be obtained.

Tensile results of these specimens, given in Table 12, indicate that the ductility of welded and aged samples is close to the base metal property. The ductility of the longitudinal welds is close to the 10.5% ductility of the base metal, averaging 7.5 and 10% for the GTA and EB welds respectively. Longitudinal specimens force all weld zones to strain equally. Hence, they expose low-ductility zones. In this light, these tests indicate that joint ductility was good. The small difference between the weld and base metal ductilities suggests that the 950°F - 4-hour age is near the optimum treatment.

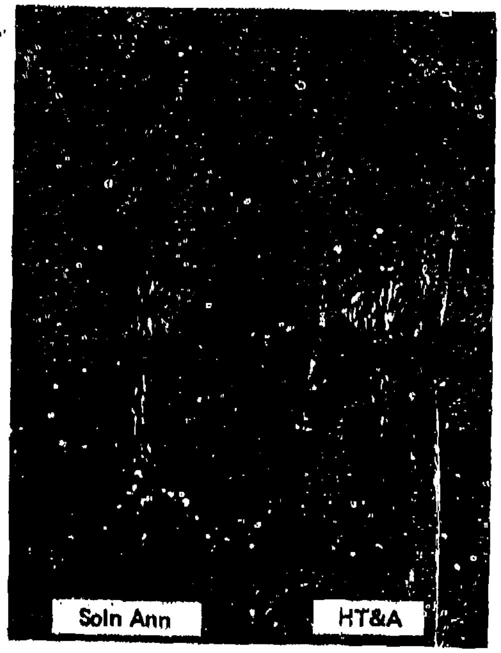
Transverse ductilities were somewhat lower than in the longitudinal direction, but are considered very acceptable for the strength levels obtained.

Weld strengths can be compared to base metal properties in Table 2. These are quite similar. Minor differences can be attributed to effects on plastic flow by the presence of weld beads.

Figure 20 shows photographs of typical tensile failures in 0.050-inch thick welded-and-aged material. Ductility is evident in the necking of the fractures and 45° shear failures. Fracture faces showed no flaws to which fracture at that particular point could be attributed.

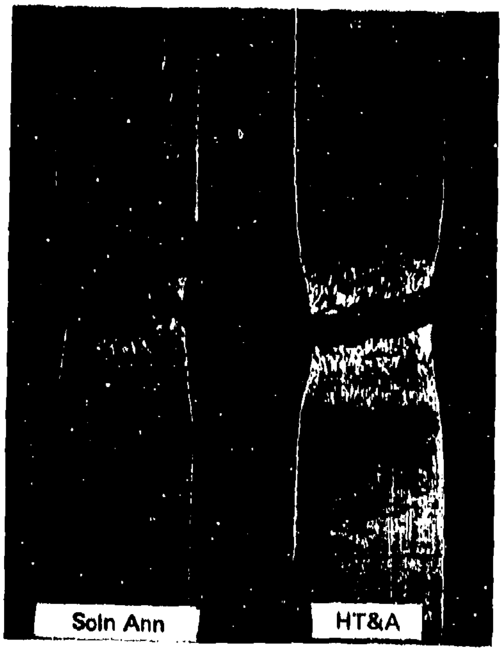
2. TASK III - 0.100-INCH THICK MATERIAL - MECHANICAL PROPERTIES

0.100-inch thick material was first GTA welded in the solution annealed condition. Half of the welded panels were machined and tested in the as-welded condition and the other half was aged for four hours at 950°F, then machined and tested. Tensile test results are given in Table 13. Figure 21 shows photographs of typical tensile fractures in 0.100-inch thick welded - and - aged material.



Longitudinal GTA Welds.
Base Metal Condition is Indicated.

Longitudinal EB Welds.

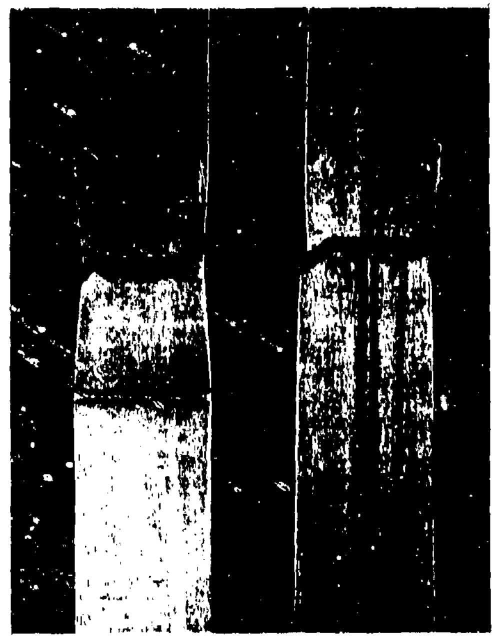


Transverse GTA Welds.

Transverse EB Welds
Mag.: 1.6X

Figure 19. Tensile Tests of As-Welded Welds In 0.050-in. Gage Ti-15V-3Cr-3Al-3Sn Sheet

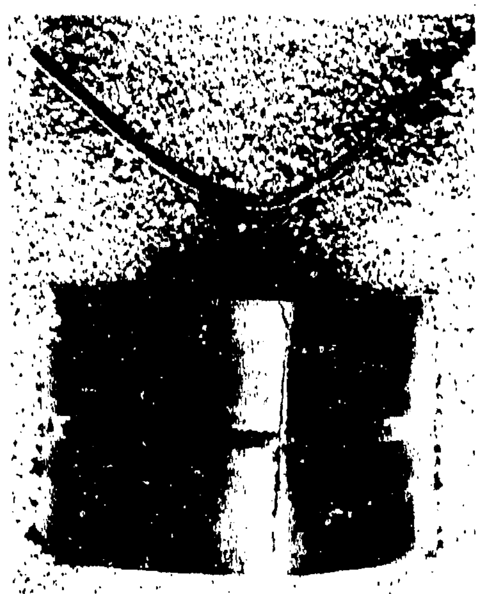
Typical GTA Tensile Specimens.



Typical EB Tensile Specimens.

Mag., all views: 1.6X

GTA Weld Bend Tests.



EB Weld Bend Tests.

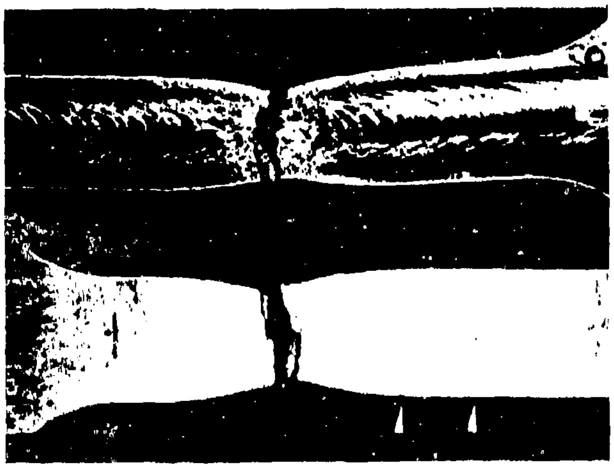
Base Metal Bend Tests.

Figure 20. Free-Bend and Tensile Tests in 0.050-in. Ti-15V-3Cr-3Al-3Sn; Solution Heat-Treated, Welded, Then Aged 950°F-4 Hours

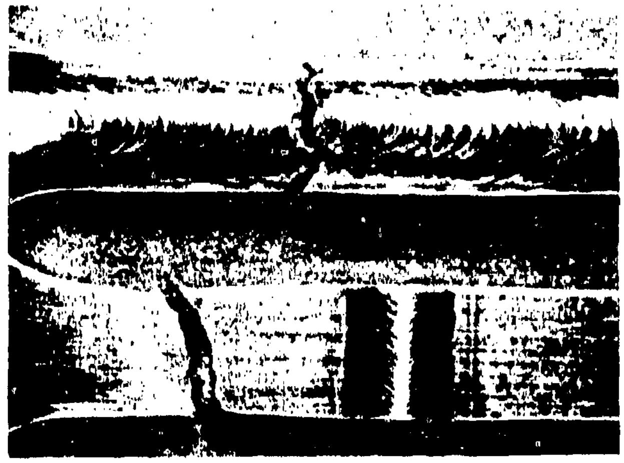
TABLE 13
MECHANICAL PROPERTIES
0.100 INCH THICK MATERIAL

Heat No.	Gage (In.)	Condition	Rolling and Weld Direction	Ult Strength ksi	Ult Strength MPa	Yield Strength ksi	Yield Strength MPa	Elongation % 2 in. or 50 mm	Longitudinal Bend (XT) Pass	Longitudinal Bend (XT) Fail
V5031	0.100	SA + EB Weld	L	110	758	98	675	16	0.6	
			L	114	786	101	696	21		
			L	113	779	102	703	20		
			T	116	799	116	799	13	0.6	
			T	116	799	115	792	13		
			T	115	792	114	785	13		
		SA + EB Weld + Age - 950°F - 4 hr	L	166	1130	150	1034	7	7.5	6.3
			L	170	1171	154	1061	9	7.5	7.0
			L	171	1178	156	1068	7		
			T	170	1171	157	1081	3		
			T	169	1164	155	1068	4		
			T	168	1157	155	1068	4		
		SA + EB Weld Age 1000°F - 4 hr	L	159	1095	145	999	10	7.5	7.0
			L	154	1161	138	951	9	7.5	7.0
			L	163	1123	145	999	9		
			T	160	1102	146	1006	8		
			T	161	1109	146	1006	10		
			T	160	1102	146	1006	9		
		SA + EB Weld Age - 1050°F - 4 hr	L	153	1054	135	930	12	5.0	4.4
			L	153	1047	133	916	12	6.0	5.6
			L	150	1034	132	909	12		
			T	153	1054	140	965	9		
			T	154	1061	141	972	9		
			T	153	1054	140	965	9		
		SA - GTA Weld	L	110	758	105	723	13	0.6	
			L	104	716	98	675	11	0.6	
			L	108	744	104	716	12		
			T	110	758	107	737	10		
			T	111	765	109	751	12		
			T	110	758	109	751	11		
		SA + GTA Weld + Age 950°F - 4 hr	L	166	1144	156	175	3	-	10
			L	176	1213	167	1151	0.5*	-	10
			L	184	1268	175	1212	3		
			T	187	1288	169	1164	4	-	
			T	185	1275	170	1171	4		
			T	181	1247	168	1157	3		
		SA + GTA Weld + Age 1000°F - 4 hr	L	172	1185	150	1033	6	-	10
			T	176	1213	152	1047	7		
			T	176	1213	152	1047	7		
		SA + GTA Weld + Age 1000°F - 8 hr	L	170	1171	148	1020	5	-	10
			L	171	1178	148	1020	8		
			T	176	1213	153	1054	7		
		SA + GTA Weld + Age 1050°F - 4 hr	L	161	1109	152	1047	4	-	10
			L	161	1109	149	1026	7	-	10
			L	164	1130	153	1054	7		
			T	166	1144	151	1040	8		
			T	169	1164	151	1040	8		
			T	168	1158	149	1026	7		

* - Broke outside gage mark.

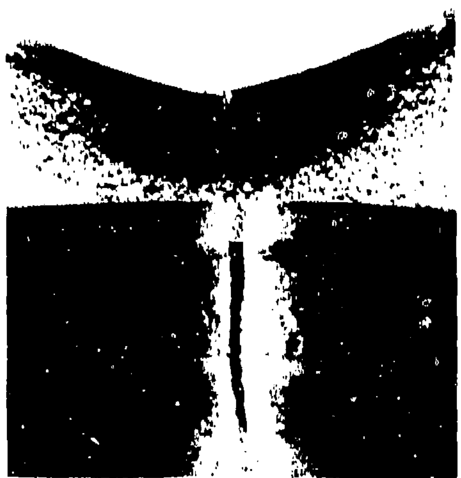


Tensile Specimens of GTA weld in as-welded condition. Weld lies between arrows.



Joints aged at 950°F after welding

As-welded



Aged 900°F

Aged 950°F

The longitudinal GTA weld on these free-bend pieces was machined flush. Magnification all photos: 1.6X

Figure 21. Free-Bend and Tensile Tests of GTA Welds in Solution Heat-Treated 0.100-in. Ti-15V-3Cr-3Al-3Sn. Heat No. V5031

The bars in the as-welded condition had high elongations (10-13 percent) and moderate tensile strengths (103.5 to 110.2 ksi for longitudinal welds and 110.1 to 110.6 ksi for transverse welds). Fractures in the transverse welds occurred in the weld in two cases and in the base metal near the edge of the weld in the third.

Tensile specimens in the welded-and-aged condition had elongations of 3 percent in the longitudinal direction and 2.5 to 4 percent in the transverse direction. Corresponding tensile strengths were high for these specimens (166.0 to 183.8 ksi in the longitudinal direction and 181.3 to 187.4 ksi in the transverse direction).

The tensile test results of the 0.100-inch thick material show considerably higher strengths in the aged condition than the 0.050-inch thick material even though both sets of panels were aged for four hours at 950°F. The only difference known in this laboratory rolled material is the amount of cold work received in the 0.050-inch versus the 0.100-inch thick materials.

Bend tests were made from the weldments that were aged at 950°F. These results are also shown in Table 13. Specimens were one inch wide by two inches long, with the weld running lengthwise. High quality specimen edges are needed to get good bend radii in aged specimens so these were cut slowly on a wet cutoff wheel and the edges were rounded on a fine belt sander. The top of the weld was flat and so was left unaltered. The melt-thru, about 0.010-inch, was ground flush. Bends were made with the top in tension (face bends).

Bending was started in a guided bend around a 2-inch diameter cylinder (i.e., a 10T radius), then with progressively smaller cylinders down to a 1-inch diameter. Below this, the specimen was end loaded in a vise with the radius being measured frequently by comparison to rods.

As-welded pieces and the solution annealed base metal were very ductile, remaining crack-free when the test was halted at 0.6T radius.

The welded-and-aged specimens broke before the 10T radius was reached. The second specimen was unloaded several times and almost no permanent deformation was obtained prior to its breaking while working toward the 10T radius. This behaviour in bend testing was not unexpected in view of strengths and ductilities shown by tensile specimens.

Before additional GTA weldments were made, the next group of specimens had been prepared for test by electron beam welding, so it was decided to age these specimens at 1000 and 1050°F as well as 950°F to determine if the higher aging temperatures produced a strength/ductility combination equivalent to 0.050-inch sheet welded and aged at 950°F. Base metal aging response was also determined (Table 2). Surprisingly, the EB welded material did not age to the high strength levels expected at 950°F, and aging at 1000 and 1050°F lowered strengths still further to levels considered undesirably low. Tensile ductility of all these specimens is satisfactory for the strengths obtained. Bend ductility values are given in Table 13; as-welded material has extremely good bend ductility and aged bends are higher, as expected. All of these bend test results are considered normal.

Base metal tensile tests (Table 2) confirm that aging response of the 0.100-inch sheet is basically the same as 0.050-inch sheet. Additional GTA weldments were aged at 1000 and 1050°F for four hours and tested. These data are also shown in Table 13 and confirm earlier results. Bend tests also confirm the earlier high bend test values.

The different heat inputs of EB and GTA welding were recognized as a possible cause of the anomalous behavior, but it was discounted earlier because EB- and GTA-welded 0.050-inch thick specimens displayed essentially the same aging behaviour. However, it appeared that the larger GTA weld bead and heat-affected zone in 0.100-inch sheet (with respect to the width and gage length of the standard tensile specimen) was a possible cause of the high aged strengths. It was also noted that bend ductility of 0.100-inch GTA aged welds was not as good as bend ductility of 0.100-inch EB aged welds. It was then planned to test a group of aged 0.100-inch transverse weld specimens having an extended gage length (4 inches) to determine if a more normal tensile strength value is obtained. The special 4-inch gage length specimens and a set of normal 2-inch gage length specimens were machined and tested. The results of these tests are shown in Table 14.

TABLE 14
MECHANICAL PROPERTIES
0.100 INCH THICK MATERIAL

Heat No.	Gage (In.)	Condition	Rolling and Weld Direction	Ult Strength		Yield Strength		Elongation %	Longitudinal Bend (XT)	
				ksi	MPa	ksi	MPa	2 In. or 50 mm	Pass	Fail
V5031	0.100	SA + GTA Weld + Age 1000°F - 8 hr	T	165	1137	147	1013	8		
		2 In. Gage Length	T	164	1130	144	992	8		
		SA + GTA Weld + Age - 1000°F - 8 hr	T	163	1123	147	1013	6		
		4 In. Gage Length	T	164	1130	147	1013	7		

It will be noted that strength levels of the 4-inch gage length specimens are almost identical to those of 2-inch gage length specimens welded and aged at the same time. This eliminates the higher heat input of GTA welding as the cause of the anomalous aging response. A vacuum furnace had been used for aging of all test specimens. This furnace has been used many times satisfactorily for heat treating titanium alloys, but aging operations were transferred to an air-circulating furnace because of the possibility that temperature non-uniformity in the vacuum furnace may be the cause of aged property differences.

As a part of Task III, the 0.100-inch thick material was welded with filler wire (Table 11). The filler material used was Ti-15V-3CR-3Al-3Sn, 1/16-inch diameter centerless ground wire furnished by AFML. The weld joint used was a "V" groove with a 60° included angle and a 0.020-inch land on the bottom side.

Three sets of test panels were welded with no anomalies in the welding of this material with wire. The material is considered to have good weldability. The samples were tested in the following conditions:

1) Solution Annealed - GTA welded
2) Solution Annealed - GTA welded - Aged at 900°F for 8 hours
3) Solution Annealed - GTA welded - Aged at 950°F for 8 hours

The weld reinforcement from these filler-metal-added welds was ground flush for the transverse tensile specimens so that the weld stress would be as high as the base metal stress. Nevertheless, all transverse weld specimens failed in the base metal about 0.5 inch from the edge of the weld. This is beyond the heat affected zone.

The longitudinal weld specimens were left with reinforcement intact. The elongation probably would have been improved if the reinforcement had been removed, since the weld bead was irregular on some specimens. Test results of these specimens are shown in Table 15.

TABLE 15
MECHANICAL PROPERTIES
0.100 INCH THICK WITH FILLER WIRE

Heat No.	Gage (In.)	Condition	Rolling and Weld Direction	Ult Strength		Yield Strength		Elongation % 2 in. or 50 mm	Longitudinal Bend (XT)	
				ksi	MPa	ksi	MPa		Pass	Fail
P2360	0.100	SA + GTA Weld with Filler Wire as Welded	L	120	827	110	728	13	0.6	–
			L	120	827	107	737	13	0.6	
			L	121	834	110	758	17		
			T	114	785	109	751	10		
			T	116	799	109	751	10		
			T	114	785	107	737	11		
		SA + GTA Weld with Filler Wire Age 900°F - 8 hr	L	204	1406	188	1295	4	7.5	7
			L	196	1350	183	1261	1*	14	11
			L	204	1406	173	1192	2*		
			T	190	1309	170	1171	5		
			T	190	1309	173	1192	6		
			T	191	1316	173	1192	5		
		SA + GTA Weld with Filler Wire Age 950°F - 8 hr	L	189	1302	150	1034	5	7.5	7
			L	191	1316	174	1199	5	7.5	6.5
			L	190	1309	177	1220	4		
			T	176	1213	147	1013	6		
			T	176	1213	–	–	6		
			T	178	1226	157	1082	7		

*- Broke outside gage marks.

These GTA welds, because of filler metal addition, were reinforced enough to require machining of both surfaces to produce unreinforced bend specimens. Because of the similarity in appearance between upper and lower surface, five of the six specimens were inadvertently bent with root side in tension. This is contrary to practice since all 0.100-inch bends have heretofore been made with the weld face in tension.

The face bend evidently is a more severe test of ductility than the root bend for GTA welds in this alloy. The one specimen which received a face bend failed at 11.0T bend radius compared to its duplicate which failed at 7.0T in the root bend mode. The 11.0T radius appears normal, in view of the high tensile strength of the companion 900°F tensile tests.

An earlier GTA weld aged at 950°F in the first lot of material failed at 10.0T radius in a face bend test. Hence radii of 10 or 11T appear normal for the low-temperature age.

3. TASK IV - 0.300-INCH THICK MATERIAL MECHANICAL PROPERTIES

A series of 0.300-inch thick specimens were EB welded from the purchased plate and aged, after welding, at 900, 950, and 1000°F for testing. A group of six specimens (3L, 3T) aged 8 hours at 950°F were first to be tested. Unfortunately, five specimens of this group were tested before it was realized that weld penetration was not complete, and was resulting in premature failures. Approximately 0.050-inch was machined from the surface containing the lack-of-penetration of remaining specimens before testing was continued. Test data (Table 16) show normal combinations of strength and ductility for this alloy and are consistent with results obtained previously on 0.050 and 0.100-inch thick sheet.

Machining the underside of 0.300-inch thick EB welds before testing was continued throughout the program. An alternative (one which would be used for production parts) would be to machine an upstanding lip on the top of one of the mating parts. This provides filler metal for the top of the weld to eliminate undercutting and permits the use of sufficient power to fully penetrate to the bottom of the 0.300-inch thick joint. However, this is an expensive alternative for a test program. Machining off the bead undersurface provides equally valid data.

TABLE 16
MECHANICAL PROPERTIES
0.300 INCH THICK MATERIAL

Heat No.	Gage (In.)	Condition	Rolling and Weld Direction	Ult Strength		Yield Strength		Elongation % 2 in. or 50 mm
				ksi	MPa	ksi	MPa	
P2360	0.300	SA + EB Weld + Age - 900°F - 8 hr	L	184	1268	171	1178	4
			L	180	1240	168	1158	4
			L	189	1302	175	1206	4
			T	179	1233	163	1123	6
			T	178		161	1109	6
			T	182	1254	162	1116	6
		SA + EB Weld + Age 950°F - 8 hr	T	173	1192	154	1061	7
		SA + EB Weld + Age - 1000°F - 8 hr	L	167	1151	150	1034	7
			L	168	1158	151	1040	6
			L	162	1116	156	1075	5
			T	162	1116	144	992	8
			T	164	1130	141	971	7
			T	159	1096	142	978	8

4. TASK V - OPTIMUM WELDMENT CHARACTERIZATION

This task constitutes a property characterization of weldments in the Ti-15V-3Cr-3Al-3Sn alloy. Welding processes (EB and GTA) established under Tasks II, III, and IV in three gage thicknesses (0.050, 0.100, and 0.300 inch) were used. Two target strength levels - 150,000 psi minimum yield strength and 165,000 psi minimum yield strength – were chosen for the characterization in order to provide data at both medium - and high - strengths.

Longitudinal and transverse tensile and bend tests were made for all test conditions. In addition, corresponding notched tensile tests, fracture toughness (0.300 inch thick only), and crack growth tests were made. Hardness traverses and metallographic examinations were made of typical cross-sections. The complete test matrix is shown in Table 17.

TABLE 17
TEST MATRIX FOR TASK V – OPTIMUM WELDMENT CHARACTERIZATION – Ti-15V-3Cr-3A1-3Sn

Weldment Condition	Mechanical Properties							Metallurgical	
	Tensile		Bend		Notched Tensile One Direction	Fracture Toughness One Direction	da/dn One Direction	Harness Traverse	Micro
	Long	Trans	Long	Trans*					
0.050 in. thick material - number of tests to be run									
Soln annealed - GTAW	3	3	3	1				1	1
Soln annealed - GTAW - Aged - 900°F	3	3	3	1	2		2	1	1
Soln annealed - GTAW - Aged - 925°F	3	3	3	1	2		2	1	1
Soln annealed - EBW	3	3	3	1				1	1
Soln annealed - EBW - Aged - 900°F	3	3	3	1	2		2	1	1
Soln annealed - EBW - Aged - 925°F	3	3	3	1	2		2	1	1
Total	18	18	18	6	8		8	6	6
0.100 in. thick material - number of tests to be run									
Soln annealed - GTAW	3	3	3	1				1	1
Soln annealed - GTAW - Aged - 900°F	3	3	3	1	2		2	1	1
Soln annealed - GTAW - Aged - 950°F	3	3	3	1	2		2	1	1
Soln annealed - GTAW - with wire	3	3	3	1				1	1
Soln annealed - GTAW - with wire - 900°F	3	3	3	1	2		2	1	1
Soln annealed - GTAW - with wire - 950°F	3	3	3	1	2		2	1	1
Soln annealed - EBW	3	3	3	1				1	1
Soln annealed - EBW - Aged - 900°F	3	3	3	1	2		2	1	1
Soln annealed - EBW - Aged - 950°F	3	3	3	1	2		2	1	1
Total	27	27	27	9	12		12	9	9
0.300 in. thick material - number of tests to be run									
Soln annealed - EBW	3	3			3	2	2	1	1
Soln annealed - EBW - Aged - 900°F	3	3			3	2	2	1	1
Soln annealed - EBW - Aged - 950°F	3	3			3	2	2	1	1
Total	9	9			9	6	6	3	3
Total test for program	108 Tensiles		60 Bend		29 Notched Tensiles	6 Fracture Toughness Compact Tension	26 - da/dn	18 Hardness Travers	18 Micros

Solution treated - 1450°F - 10 minutes - air cooled
Aging - at temperature for 8 hours - air cooled
EBW - Electron Beam welded
GTAW - Gas Tungsten Arc Welded

Long. - Longitudinal to weld and rolling direction
Trans. - Transverse to weld and rolling direction

*Transverse Bend Tests will be done if significant data can be obtained

Tensile and bend tests were made in accordance with the description given in a previous section of this report.

a. **Tensile Tests**

Welded specimens were tested in both transverse and longitudinal directions with respect to the weld bead. All welds were made parallel to the rolling direction of the sheet and plate. Tests were conducted using specimens of full ASTM specification size to ensure that valid reproducible data were obtained.

Tensile test results on weldments are shown in Tables 18, 19 and 20. Results in all cases were similar to those reported in the weld parameter establishment portion of this program. The as-welded

TABLE 18
MECHANICAL PROPERTIES OF WELDMENTS IN 0.050 IN.
Ti-15V-3Cr-3Al-3Sn SHEET (HEAT P2360)

Condition	Rolling and Weld Direction	Ult Strength		Yield Strength		Elongation (%) 2 in. or 50 mm	Longitudinal Bend (XT)	
		ksi	MPa	ksi	MPa		Pass	Fail
SA + EB	L	113.3	781.2	102.4	706.0	18	1.2	0.9
	L	113.7	784.0	99.0	682.6	14	1.2	0.9
	L	117.2	808.1	103.6	714.3	14	1.2	0.9
	T	114.1	786.7	107.4	740.5	14	0.8	0.6
	T	114.6	790.2	107.6	741.9	13		
	T	114.3	780.1	106.5	734.3	12		
SA + EB + 900F, 8 hrs	L	181.5	1251.4	161.9	1116.3	6	10	8
	L	181.1	1248.7	162.8	1122.5	9	9	8
	L	177.4	1223.2	161.0	1110.1	3	9	8
	T	188.5	1290.7	170.8	1177.7	5	13.8	12.5
	T	183.2	1263.2	165.8	1143.2	5		
	T	183.6	1265.9	166.3	1146.6	5		
SA + EB + 925F, 8 hrs	L	181.4	1250.8	162.4	1119.7	7	8.8	7.5
	L	181.8	1253.5	156.4	1078.4	6	8.8	7.5
	L	182.1	1255.6	165.2	1139.1	7	8.8	7.5
	T	181.3	1250.1	163.6	1280.0	9	17.5	15
	T	180.7	1245.9	161.3	1112.2	8		
	T	180.3	1243.2	163.5	1127.3	7		
SA + GTA	L	117.4	809.5	102.5	706.7	13	1.2	0.9
	L	116.7	804.6	102.2	704.7	13	1.2	0.9
	L	117.9	812.9	102.4	706.0	15	0.6	0.6
	T	115.0	792.9	109.3	753.6	13	0.6	
	T	118.2	815.0	109.2	752.9	11		
	T	117.0	806.7	111.1	766.0	10		
SA + GTA + 900F, 8 hrs	L	187.5	1292.8	174.6	1203.9	4	11.2	10
	L	186.6	1286.6	178.0	1227.3	4	11.2	10.6
	L	189.0	1303.2	176.7	1218.3	4	11.2	10.6
	T	189.0	1305.9	172.2	1187.3	6	10	9
	T	187.9	1295.6	170.9	1178.4	7		
	T	186.5	1285.9	170.7	1177.0	6		
SA + GTA + 925F, 8 hrs	L	183.9	1268.0	174.6	1203.9	3.5	11.2	10
	L	182.1	1255.6	178.9	1233.5	4	11.2	10.6
	L	181.1	1248.7	175.5	1210.1	3.5	11.2	10.6
	T	179.5	1237.7	173.8	1198.4	7	10	9
	T	177.4	1223.2	172.6	1190.1	6		
	T	177.9	1226.6	167.1	1152.2	6		

TABLE 19
MECHANICAL PROPERTIES OF WELDMENTS IN 0.100 IN.
Ti-15V-3Cr-3Al-3Sn SHEET (HEAT P2360)

Condition	Rolling and Weld Direction	Ultimate Tensile Strength		Yield Strength		Elongation (%) 2 in. or 50 mm	Bend (XT)	
		ksi	MPa	ksi	MPa		Pass	Fail
SA + EB	L	118.0	813.6	101.0	696.4	13	0.6	-
	L	117.7	811.5	102.8	708.8	14	0.6	-
	L	117.9	812.9	104.8	722.6	13	0.6	-
	T	113.8	784.7	113.7	784.0	15	0.6	-
	T	114.6	790.2	113.7	784.0	15		
	T	114.6	790.2	113.7	784.0	15		
SA + EB + 900F, 8 hrs	L	190.6	1314.2	171.9	1185.3	6.5	9	8.7
	L	191.1	1317.6	174.2	1201.1	6	9	8.7
	L	188.8	1301.8	171.0	1179.0	6	10	9
	T	194.7	1342.5	179.5	1237.7	6	12.5	11.2
	T	194.6	1341.8	181.6	1252.1	6.5		
SA + EB + 950F, 8 hrs	L	183.2	1263.2	165.2	1139.1	7.5	7.5	7
	L	181.8	1253.5	163.9	1130.1	5.5	8.7	7.5
	L	181.2	1249.4	162.4	1119.7	6.5	.7	7.5
	T	177.4	1223.2	165.7	1142.5	8.5	9	8.7
	T	175.5	1210.1	163.4	1126.6	9		
	T	175.3	1208.7	167.1	1152.2	8		
SA + GTA	L	117.7	811.5	108.9	750.9	12	0.8	0.6
	L	118.7	818.4	106.8	736.4	13	0.6	-
	L	119.0	820.5	107.6	741.9	10	0.7	0.6
	T	116.8	805.3	111.6	769.5	12.5	0.8	0.6
	T	117.6	810.9	111.6	768.8	12		
	T	117.3	808.8	112.3	774.3	10.5		
SA + GTA + 900F, 8 hrs	L	197.1	1359.0	181.7	1252.8	2.5	15	11.3
	L	193.8	1336.3	177.0	1220.4	4.0	10	8.7
	L	194.2	1339.0	179.8	1239.7	3.5	11.3	10
	T	194.1	1338.3	176.5	1217.0	5.0	12.5	12.2
	T	194.2	1339.0	166.7	1149.4	6.5		
	T	193.3	1332.8	176.8	1219.0	5.5	7	
SA + GTA + 950F, 8 hrs	L	183.9	1268.0	170.0	1172.2	4	7.5	6.9
	L	182.3	1257.0	170.6	1176.3	4.5	9	8.7
	L	176.6	1217.7	162.4	1119.7	3.5	8.7	7.5
	T	170.1	1172.8	154.6	1066.0	7.5	8.7	7.5
	T	173.1	1193.5	-	-	6.5		
	T	171.4	1181.6	159.1	1097.0	8		
SA + GTA (filler)	L	108.0	744.7	102.8	708.8	15	0.8	0.6
	L	111.8	770.9	110.3	760.5	15	0.6	-
	L	107.1	738.5	103.4	712.9	13	0.8	0.6
	T	111.1	766.0	101.6	700.5	15	0.6	-
	T	110.8	764.0	106.8	736.4	15		
	T	110.7	763.3	102.4	706.0	17		
SA + GTA (filler) + 900F, 8 hrs	L	192.7	1328.7	181.4	1250.8	1.5	8.7	7.5
	L	182.9	1261.1	174.3	1201.8	1.0	7.5	7.0
	L	192.5	1327.3	178.1	1228.0	3.0	9.4	8.7
	T	177.5	1223.9	163.5	1127.3	1.5	-	15
	T	187.9	1295.6	172.8	1191.5	3.5		
	T	186.6	1286.6	167.5	1154.9	3.0		
SA + GTA (filler) + 950F, 8 hrs	L	182.7	1259.7	-	-	4.0	8.7	7.5
	L	178.8	1232.8	169.3	1167.3	3.0	7.0	5.6
	L	183.5	1265.2	168.5	1161.8	-	8.7	7.5
	T	162.8	1122.5	153.5	1058.4	3.0	9.4	8.7
	T	173.2	1194.2	159.0	1096.3	8.5		
	T	170.3	1174.2	150.9	1040.5	7.5		

TABLE 20
MECHANICAL PROPERTIES OF WELDMENTS IN 0.300 IN.
Ti-15V-3Cr-3Al-3Sn PLATE (HEAT P2360)

Condition	Rolling and Weld Direction	Ultimate Tensile Strength		Yield Strength		Elongation (%) 2 in. or 50 mm
		Ksi	MPa	Ksi	MPa	
SA + EB	L	117.2	808.1	102.3	705.4	18
	L	116.1	800.5	101.0	696.4	17
	L	116.6	804.0	102.0	703.3	16.5
	T	119.2	821.9	110.3	760.5	14
	T	119.5	824.0	110.7	763.3	12
	T	119.4	823.3	110.9	764.7	15
SA + EB + 900F, 8 hrs	L	190.9	1316.3	178.9	1233.5	3
	L	187.8	1294.9	171.7	1183.9	2.5
	L	187.7	1294.2	177.5	1223.9	2.5
	T	192.9	1330.0	177.0	1220.4	2.5
	T	186.5	1285.9	173.8	1198.4	2.5
	T	180.2	1242.5	171.4	1181.8	3.0
SA + EB + 950F, 8 hrs	L	178.4	1230.1	159.9	1102.5	4.5
	L	180.1	1241.8	158.1	1090.1	5.0
	L	176.6	1217.7	154.7	1066.7	6.5
	T	182.9	1261.1	167.0	1151.5	3.5
	T	179.4	1237.0	164.6	1134.9	3.5
	T	180.3	1243.2	162.3	1119.1	4.5

specimens were very ductile and indicate that this material could be solution annealed, welded by either EB or GTA methods, and formed to the extent that the base metal could be formed. The heat treatment response was as predicted and at the strength levels achieved the ductility is comparable to other titanium alloys.

b. Notched Tensile Strengths

Notched tensile strengths were determined in welds for all aged conditions and in base metal for the same aged conditions. Results are shown in Table 21, 22, and 23. Ratios of notched UTS/smooth bar yield strengths are shown in the tables. These values are somewhat lower than are normally reported for solution heat treated and aged Ti-6Al-4V; Reference 3 reports a ratio of 0.7 for Ti-6Al-4V heat treated to an ultimate strength level of 165 ksi. This difference is attributed mainly to the fact that this program used the ASTM specimen (Figure 22), which has a stress concentration factor higher than normal (> 16) for notched tensile tests. Also, an unusually high ratio (0.996 - 1.048, Table 23) for an unaged EB weld in Ti-15V-3Cr-3Al-3Sn suggests that the relatively high aged strength level used in this program is a contributing factor to the low ratios.

c. Fracture Toughness

Fracture toughness test results for Electron Beam welds in 0.300 in. thick plate are shown in Table 24. Invalid K_Q values were obtained in the relatively ductile as-welded condition, but valid K_{1C} values were obtained for both aged conditions. These are equivalent to K_{1C} fracture toughness values of 39.8 to 44.0 reported for solution heat treated and aged Ti-6Al-4V in Reference 4. Figure 23 shows the specimen used for fracture toughness testing.

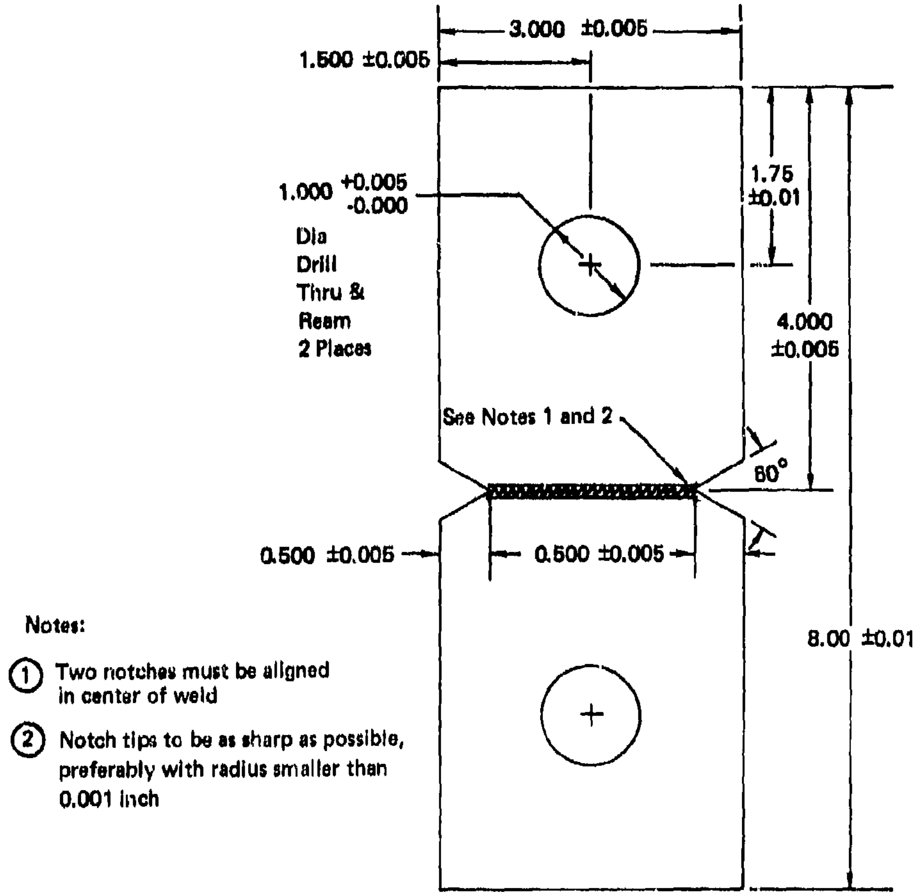


Figure 22. Sharp Edge-Notched Tensile Specimen

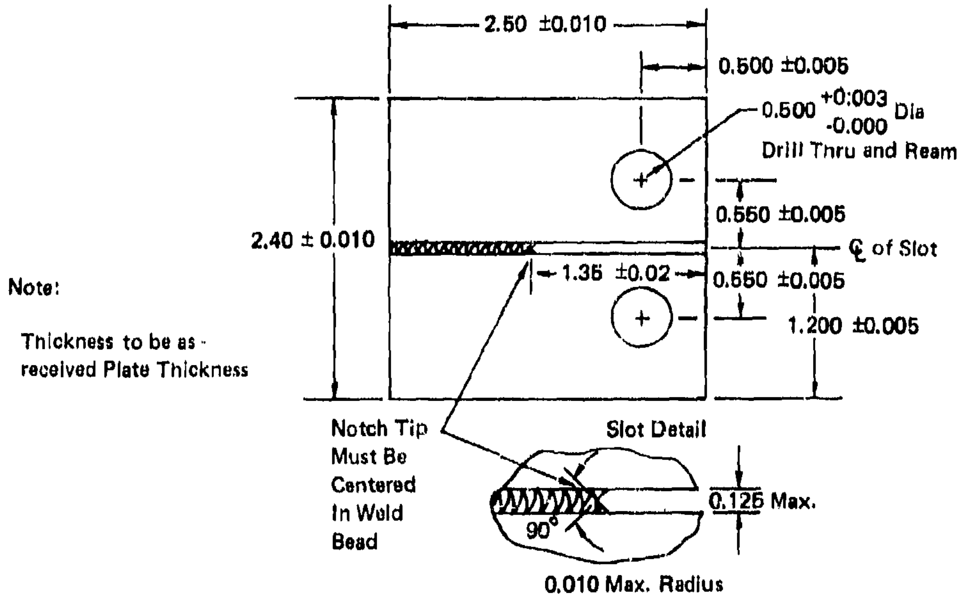


Figure 23. Compact Tension Specimen

TABLE 21

NOTCHED TENSILE STRENGTHS OF 0.050 IN. Ti-15V-3Cr-3Al-3Sn WELDMENTS (HEAT P2360)

Condition	Notched UTS		Smooth Bar YS		Ratio Notched UTS/ Yield Strength
	ksi	MPa	ksi	MPa	
Base Metal - Aged 900F, 8 hrs	73.2 72.9	504.7 502.6	164.9	1137.0	0.444 0.442
Base Metal - Aged 925F, 8 hrs	83.9 83.7	578.5 577.1	162.8	1122.5	0.516 0.514
SA + EB - Aged 900F, 8 hrs	65.5 75.6	451.6 521.3	167.6	1155.6	0.391 0.451
SA + EB - Aged 925F, 8 hrs	62.5 75.8	430.9 522.6	162.8	1122.5	0.384 0.466
SA + GTA - Aged 900F, 8 hrs	81.0 71.8	558.5 495.1	171.3	1181.1	0.473 0.419
SA + GTA - Aged 925F, 8 hrs	83.7 83.5	577.1 575.7	171.2	1180.4	0.489 0.488

TABLE 22

NOTCHED TENSILE STRENGTHS OF 0.100 IN. Ti-15V-3Cr-3Al-3Sn WELDMENTS (HEAT P2360)

Condition	Notched UTS		Smooth Bar YS		Ratio Notched UTS/ Yield Strength
	ksi	MPa	ksi	MPa	
Base Metal - Aged 900F, 8 hrs	49.3 49.4	339.9 340.6	171.2	1180.4	0.288 0.289
Base Metal - Aged 950F, 8 hrs	50.1 50.0	345.4 344.7	157.2	1083.9	0.319 0.318
SA + EB - Aged 900F, 8 hrs	66.0 72.8	455.1 502.0	180.6	1245.2	0.365 0.403
SA + EB - Aged 950F, 8 hrs	74.7 67.8	515.1 467.5	165.4	1140.4	0.452 0.410
SA + GTA - Aged 900F, 8 hrs	70.8 63.6	488.2 438.5	173.3	1194.9	0.408 0.367
SA + GTA - Aged 950F, 8 hrs	70.0 75.3	482.6 519.2	156.9	1081.8	0.446 0.480
SA + GTA (Filler) - Aged 900F, 8 hrs	62.2 57.3	428.9 395.1	170.2	1173.5	0.365 0.337
SA + GTA (Filler) - Aged 950F, 8 hrs	66.8 60.5	460.6 417.1	155.0	1068.7	0.431 0.390

d. Crack Growth

Crack growth results are shown in Figures 24 through 27 for both Electron Beam and GTA welds in 0.050 in., 0.100 in. and 0.300 in. thick material. All but one test were made in the aged condition; crack growth for an Electron Beam weld in 0.300 in. thick plate in the as-welded condition is shown in Figure 27. In some cases, no significant distinction could be made between the two aged conditions - data were therefore combined into one plot. Values for A and n for the relation $dA/dN = A(\Delta K)^n$ are shown in Table 25. Values of dA/dN for selected ΔK values are given in Table 26. Figure 28 shows the specimen used for crack growth tests. Specimens were cyclic fatigue loaded to constant load values throughout each individual test.

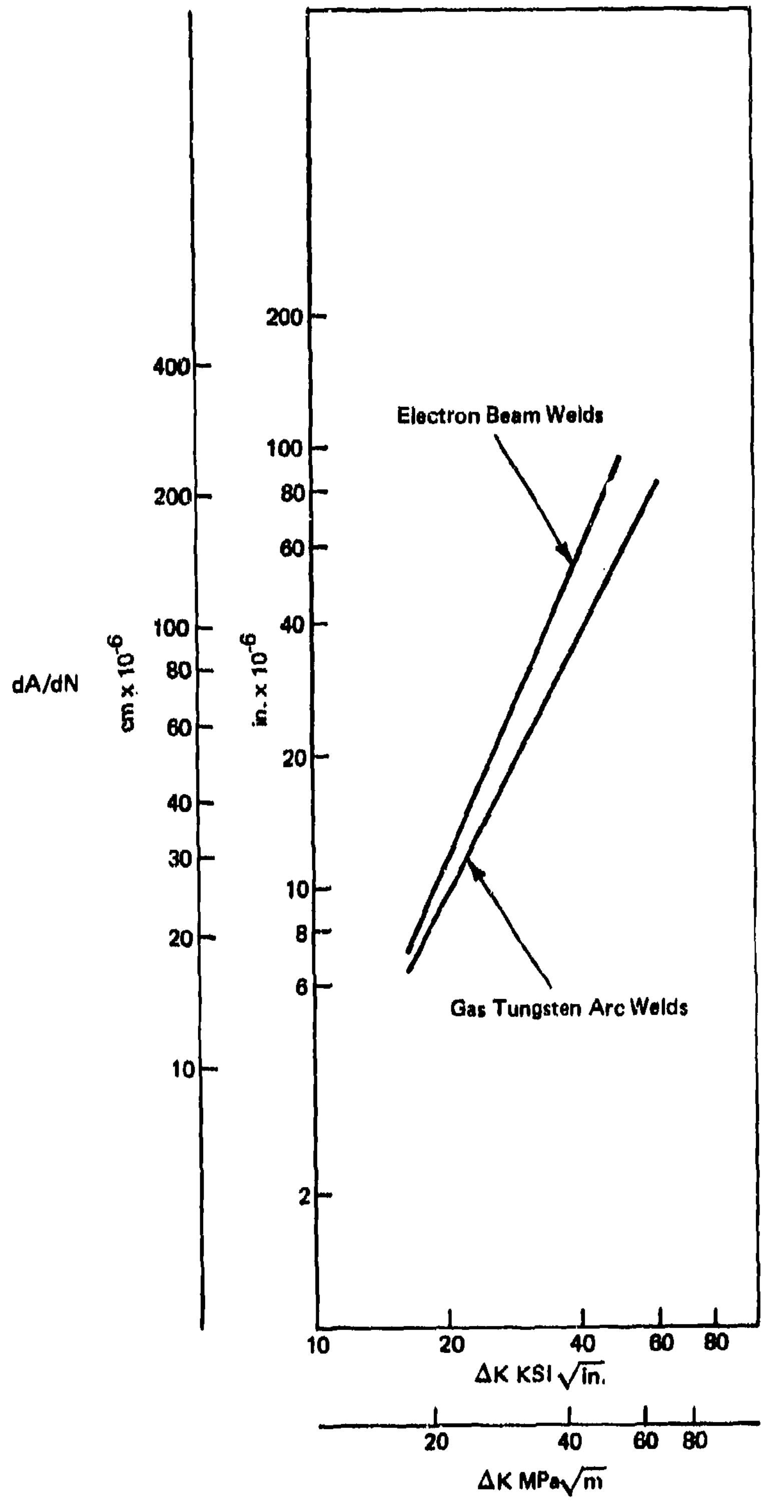


Figure 24. Crack Growth for Electron Beam and Gas Tungsten Arc Welds (Aged 900°F and 925°F for Eight Hours) in 0.050 in. Thick Ti-15V-3Cr-3Al-3Sn Sheet (Heat P2360)

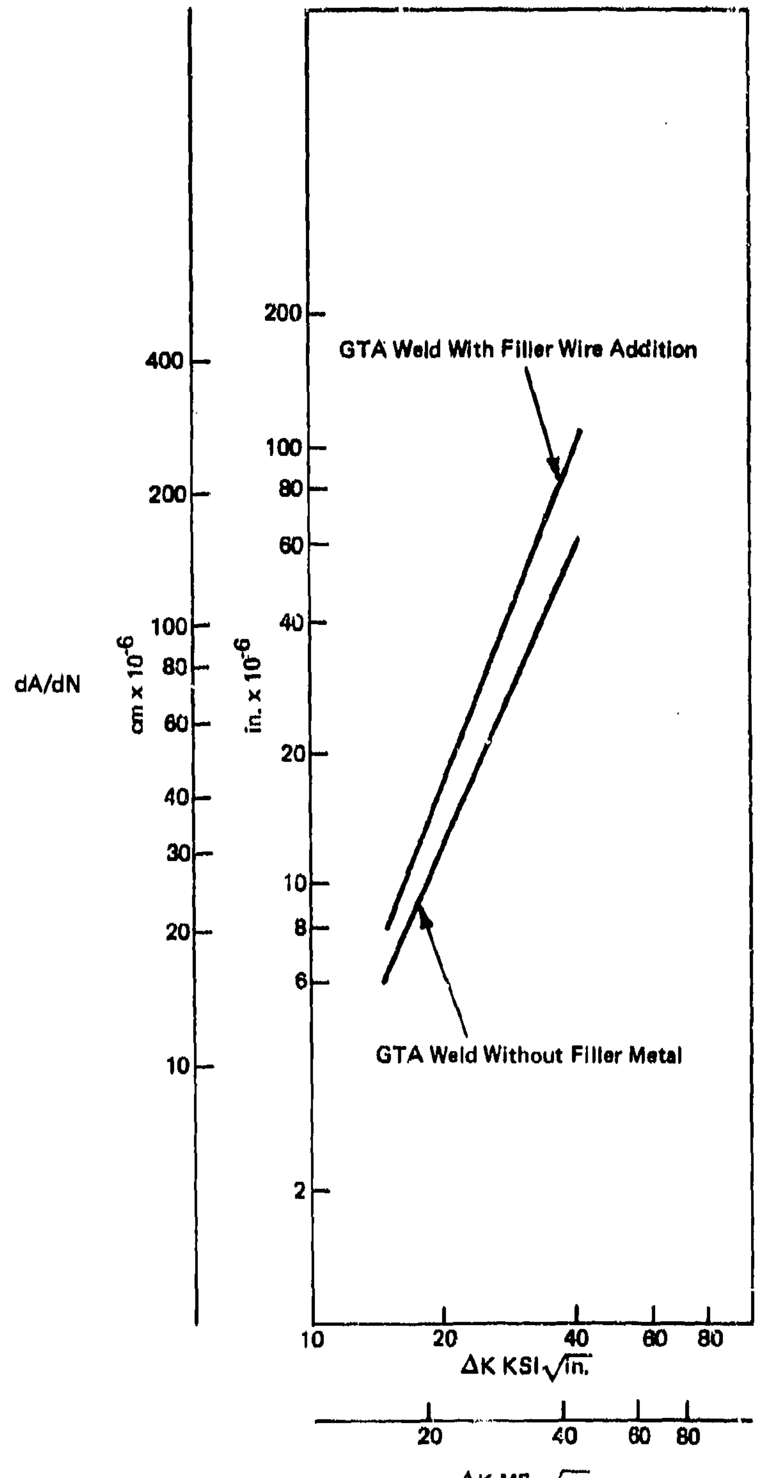


Figure 25. Crack Growth for Gas Tungsten Arc Welds (Aged at 900°F and 950°F for Eight Hours) in 0.100 in. Thick Ti-15V-3Cr-3Al-3Sn Sheet (Heat P2360)

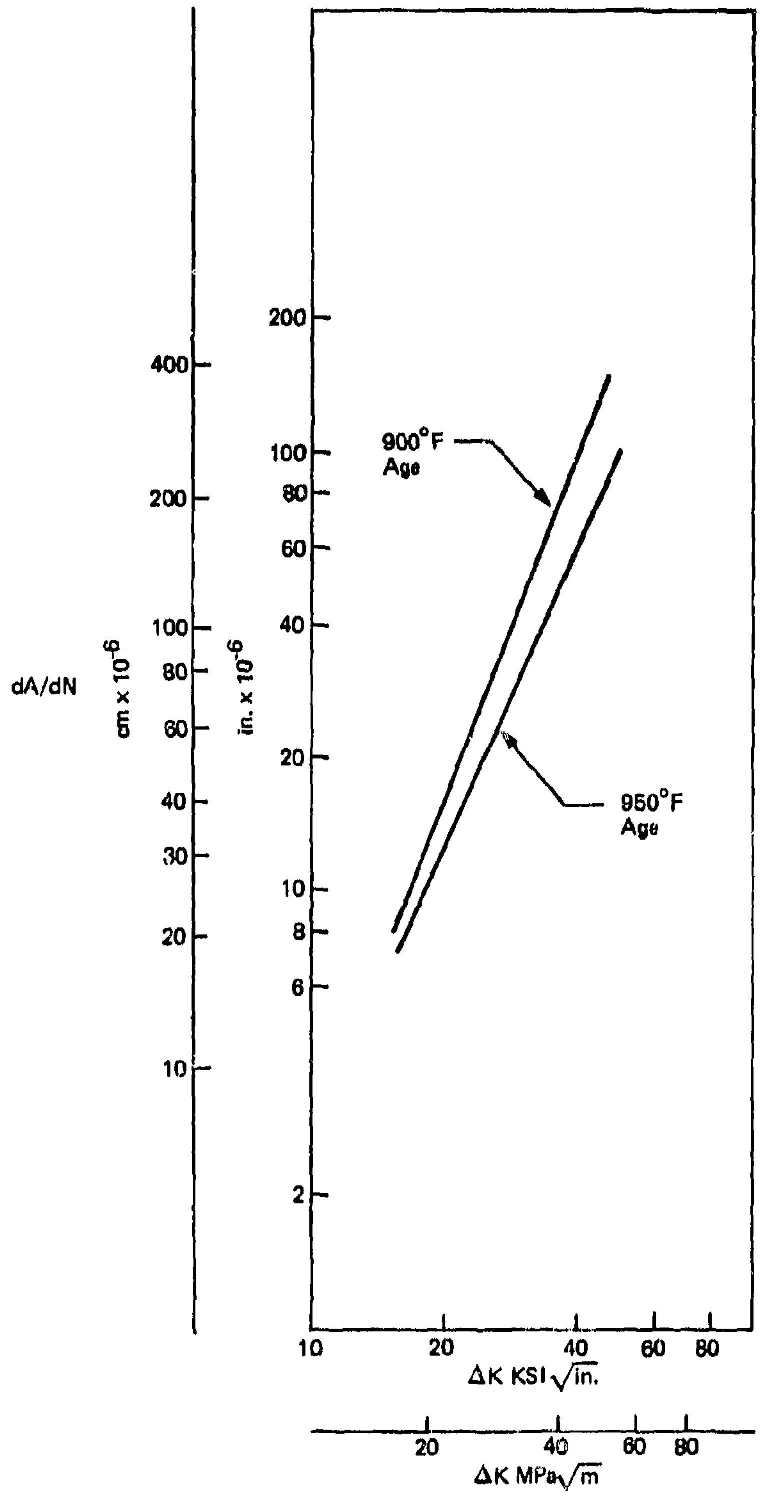


Figure 26. Crack Growth for Electron Beam Welds (Aged 900°F and 950°F for Eight Hours) in 0.100 in. Thick Ti-15V-3Cr-3Al-3Sn Sheet (Heat P2360)

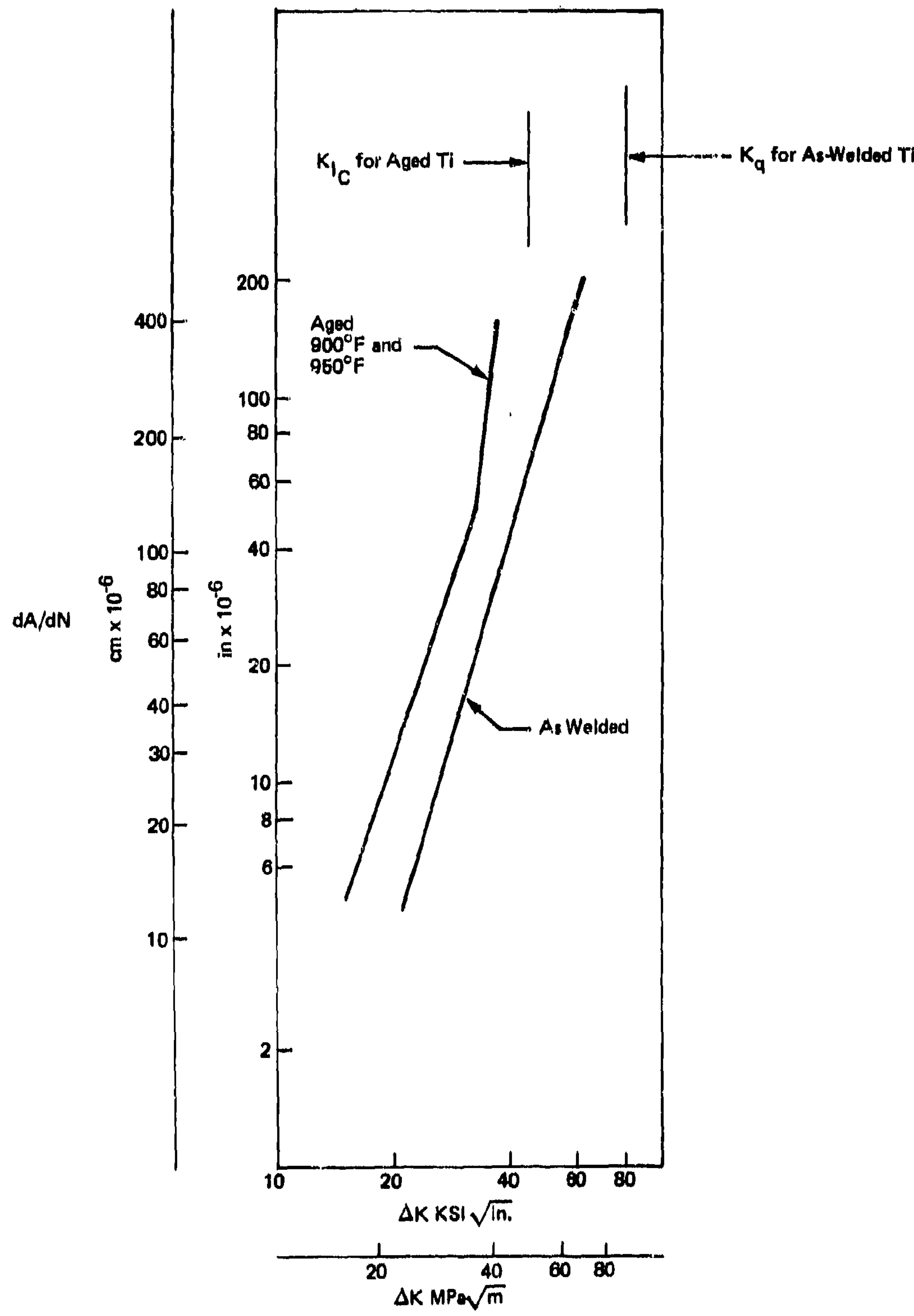


Figure 27. Crack Growth for Electron Beam Welds (As-Welded and Aged 900° and 950°F for Eight Hours) in 0.300 in. Thick Ti-15V-3Cr-3Al-3Sn Plate (Heat P2360)

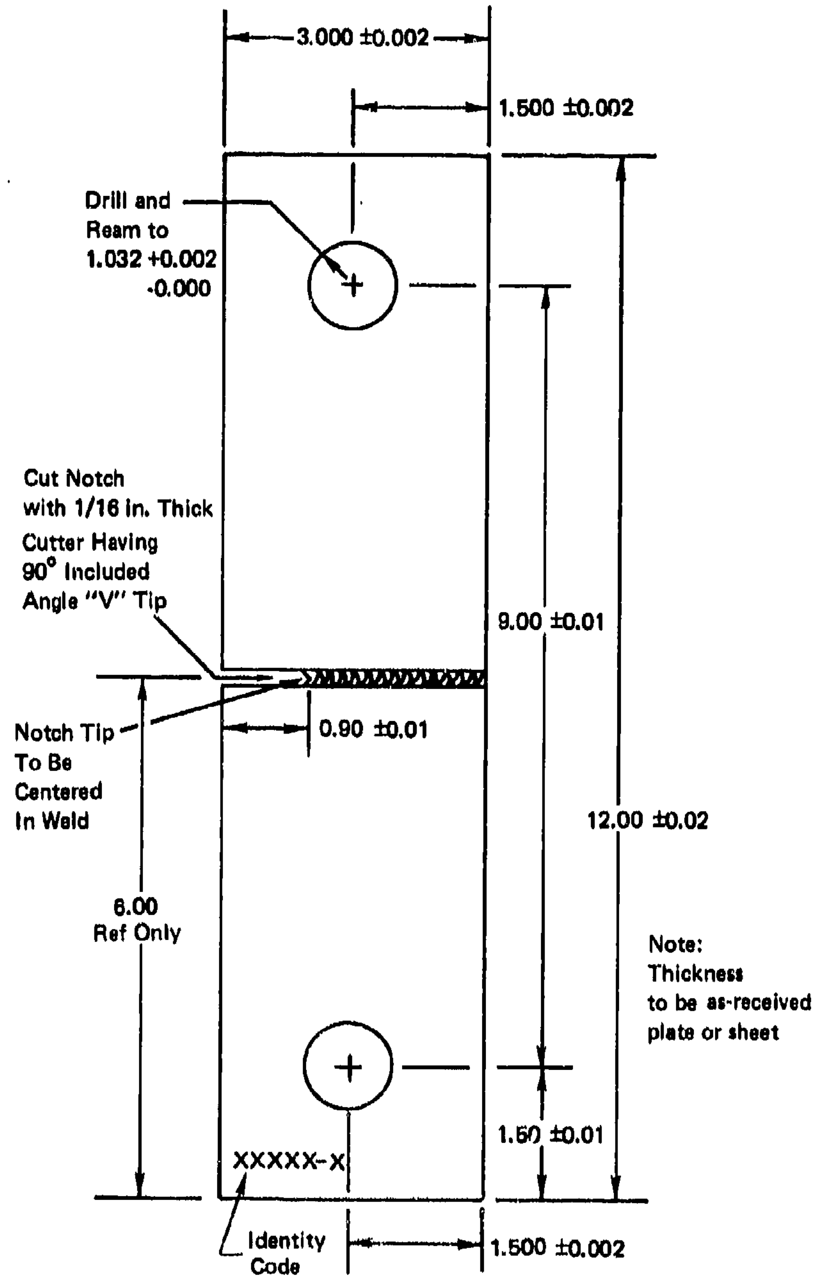


Figure 28. Single Edge-Notched Tensile Specimen

TABLE 23
NOTCHED TENSILE STRENGTHS OF 0.300 IN.
Ti-15V-3Cr-3Al-3Sn WELDMENTS (HEAT P2360)

Condition	Notched UTS		Smooth Bar YS		Ratio Notched UTS/ Yield Strength
	ksi	MPa	ksi	MPa	
Base Metal - Aged 900F, 8 hr	64.6	445.4	160.0	1103.2	0.404
Base Metal - Aged 950F, 8 hr	73.7	508.2	145.2	1001.2	0.508
SA + EB	110.2	759.8	110.6	762.6	0.996
	115.9	799.1			1.048
	112.2	773.6			1.014
SA + EB - Aged 900F, 8 hr	49.7	324.7	174.1	1200.4	0.285
	50.3	346.8			0.289
	52.8	346.1			0.303
SA + EB - Aged 950F, 8 hr	49.1	338.5	164.6	1134.9	0.298
	50.3	346.8			0.306
	53.7	370.3			0.326

TABLE 24
FRACTURE TOUGHNESS OF 0.300 IN. Ti-15V-3Cr-3Al-3Sn WELDMENTS (HEAT P2360)
(COMPACT TENSION SPECIMENS – ASTM E399 PROCEDURE)

Condition	Validity	Fracture Toughness	
		ksi$\sqrt{in.}$	MPa$\sqrt{m}$
SA + EB	Invalid K_Q	75.9	83.4
	Invalid K_Q	81.5	89.6
SA + EB + 900F, 8 hrs	Valid K_{IC}	45.4	49.9
	Valid K_{IC}	39.8	43.7
SA + EB + 950F, 8 hrs	Valid K_{IC}	46.0	50.5
	Valid K_{IC}	45.1	49.6

e. Metallographic Studies and Hardness Traverses

Metallographic cross-sections and hardness traverses of welds are shown in Figures 29 through 41.

The hardness plots of welded and aged EB welds show a hardness elevation of 10-25 Vickers numbers in the weld and heat-affected zone. Beyond the HAZ the base metal is unaltered by the welding heat.

The higher heat input in the GTA welds produces wider heat-affected zones having smoother gradients than those of the EB welds. The welded-and-aged GTA welds show a dome-shaped plot with the elevation in hardness extending beyond the ends of the apparent heat affected zone. The total elevation is 10-20 Vickers number, or about the same as that of the EB welds.

TABLE 25
A AND n VALUES FROM THE RELATION $\frac{dA}{dN} = A\,(\Delta K)^n$

Gage	Condition	A x 10^{-8}	n
0.050 in.	SA+EB - aged 900F, 8 hrs or 925F, 8 hrs	1.24	2.28
0.050 in.	SA+GTA - aged 900F, 8 hrs or 925F, 8 hrs	3.04	1.93
0.100 in.	SA+GTA - aged 900F, 8 hrs or 950F, 8 hrs	1.36	2.27
0.100 in.	SA+GTA (filler) - aged 900F, 8 hrs or 950F, 8 hrs	0.607	2.63
0.100 in.	SA+EB - aged 900F, 8 hrs	0.689	2.60
0.100 in.	SA+EB - aged 950F, 8 hrs	1.32	2.29
0.300 in.	SA+EB - aged 900F, 8 hrs or 950F, 8 hrs	0.308	2.79
0.300 in.	SA+EB	0.0137	3.45

TABLE 26
CRACK GROWTH RATES FOR SELECTED ΔK VALUES

Gage	Condition	dA/dN, in x 10^{-6}	
		ΔK = 20	ΔK = 40
0.050 in.	SA+EB - aged 900F, 8 hrs or 925F, 8 hrs	11.6	59.0
0.050 in	SA+GTA-aged 900F, 8 hrs or 925F, 8 hrs	9.6	37.5
0.100 in.	SA+GTA-aged 900F, 8 hrs or 950F, 8 hrs	12.5	59.0
0.100 in.	SA+GTA (filler)-aged 900F, 8 hrs or 950F, 8 hrs	16.5	98.0
0.100 in.	SA+EB-aged 900F, 8 hrs	16.5	100.0
0.100 in.	SA+EB - aged 950F, 8 hrs	12.5	61.0
0.300 in.	SA+EB - aged 900F, 8 hrs or 950F, 8 hrs	12.0	400*
0.300 in.	SA+EB	4.0*	46.0

*extrapolated

In two GTA specimens the hardness survey was extended 0.8 inches beyond the edge of the weld. The intent was to see if a soft zone existed which might encourage the observed failure of tensile test bars 0.5-0.7 inches from the edge of the weld. The plots of the filler-added GTA welds in 0.100 inch sheet (Figure 33) appear to reveal a softer zone -0.3-0.5 inch from the edge of the weld. The hardness drop there is rather small, about 10 Vickers numbers.

Almost all transverse weld tensile specimens failed about 0.5 inch from the edge of the weld. This included the GTA welds which appear to have a softer zone there and the EB welds which had no soft zone at the fracture site. It is believed that the fracture 0.5 inch from the edge of the weld is properly attributed to a reinforcing effect of the weld. The weld is slightly harder and in most cases slightly thicker. Hence it is more resistant to necking and accordingly acts as a reinforcement, forcing the fracture to occur at a distance from the weld.

Hardness surveys reported under the weld development program were made with a Knoop hardness tester using a 0.5 kg load. A Vickers hardness tester (10 kg load) was used for the surveys under Task V to minimize microstructural effects on hardness values.

Macrostructures of all specimens (Figures 29, 31, 33, 37, 39, and 41) were similar to those examined in the earlier weld parameter phase of the program. Heat affected zones were wider in GTA welded specimens, as expected.

A normal degree of grain growth was found in the heat affected zone immediately adjacent the weld bead and, of course, weld beads themselves were coarse grained. Heat affected zones can be easily distinguished by a light-etching characteristic caused by the alpha precipitate. Base metal microstructure consists of a finely dispersed alpha/beta mixture.

The 0.300 in. thick plate contained bands of elongated grains (Figure 39). These bands were always confined to the middle third of the plate and examination at higher magnification (Figure 41) showed that they were unrecrystallized. Microhardness tests (Vickers diamond pyramid -10 kg load) showed no difference in hardness between recrystallized and unrecrystallized material in the solution annealed condition, but unrecrystallized elongated grains were slightly harder (average of 17 DPH numbers) than neighboring grains in the aged condition. These banded areas did not have a detectable effect on properties.

As-Welded (32X)

Aged at 900F, 8 Hrs (32X)

Aged at 925F, 8 Hrs (32X)

Figure 29. Macrostructures of Electron Beam Welds in 0.050 in. Solution Annealed Ti-15V-3Cr-3Al-3Sn Sheet

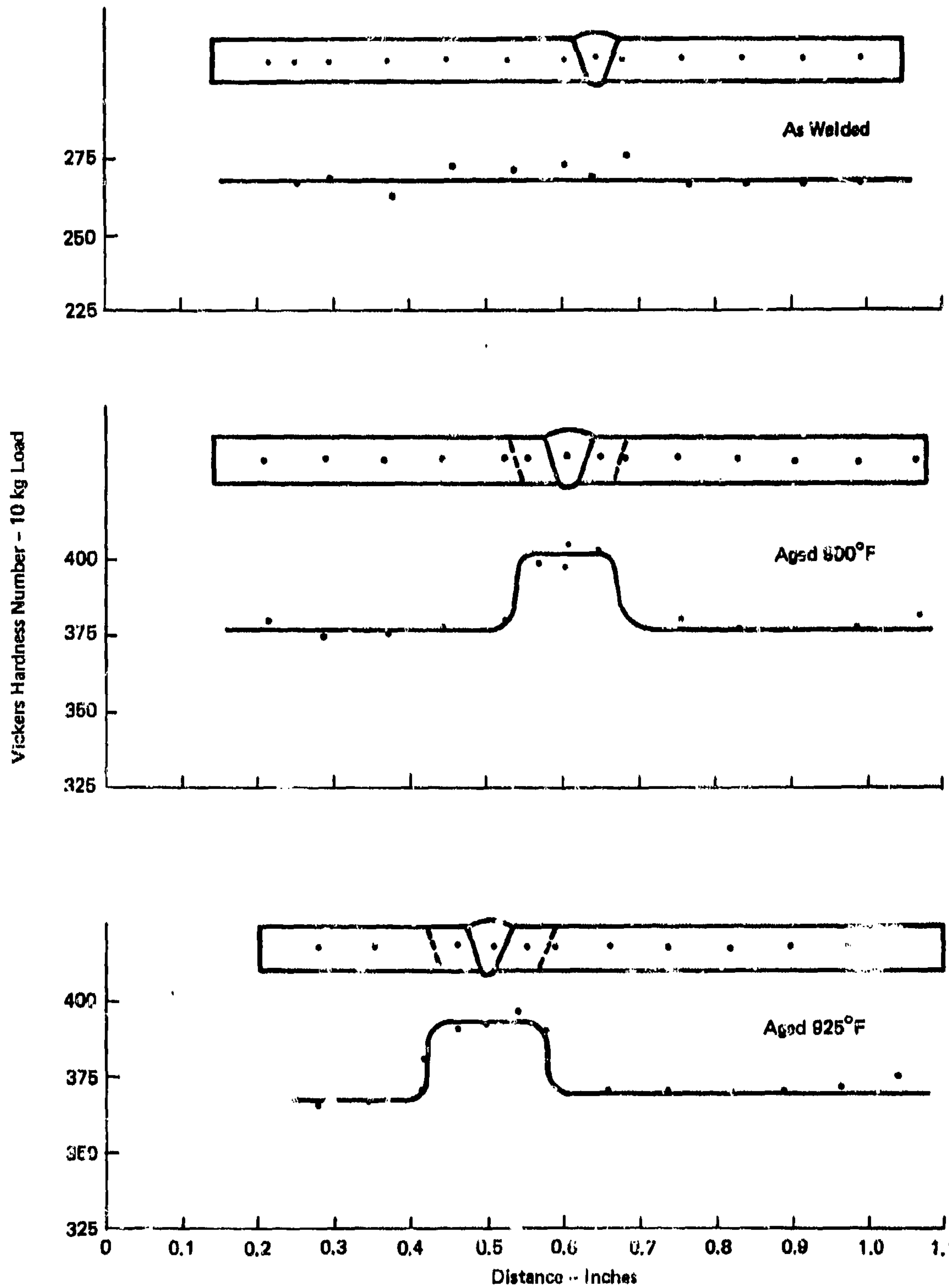
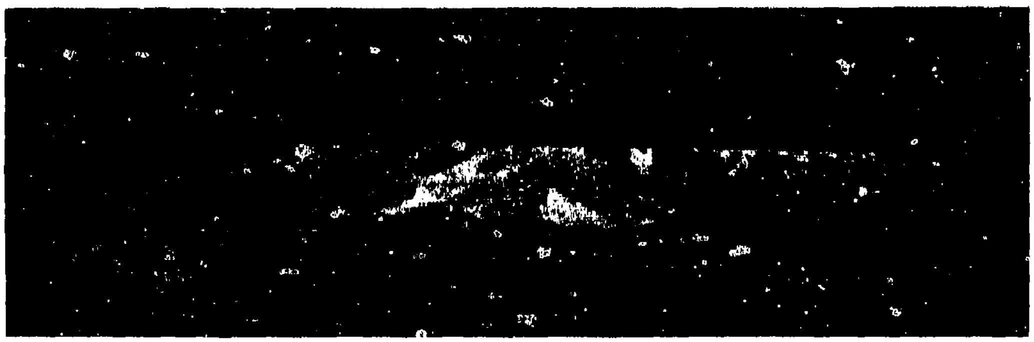


Figure 30. Hardness Surveys of EB Welds in 0.050 Inch Sheet

As-Welded (10X)



Aged at 900F, 8 Hrs (10X)

Aged at 925F, 8 Hrs (10X)

Figure 31. Macrostructures of Gas Tungsten Arc Welds in 0.050 in. Solution Annealed Ti-15V-3Cr-3Al-3Sn Sheet

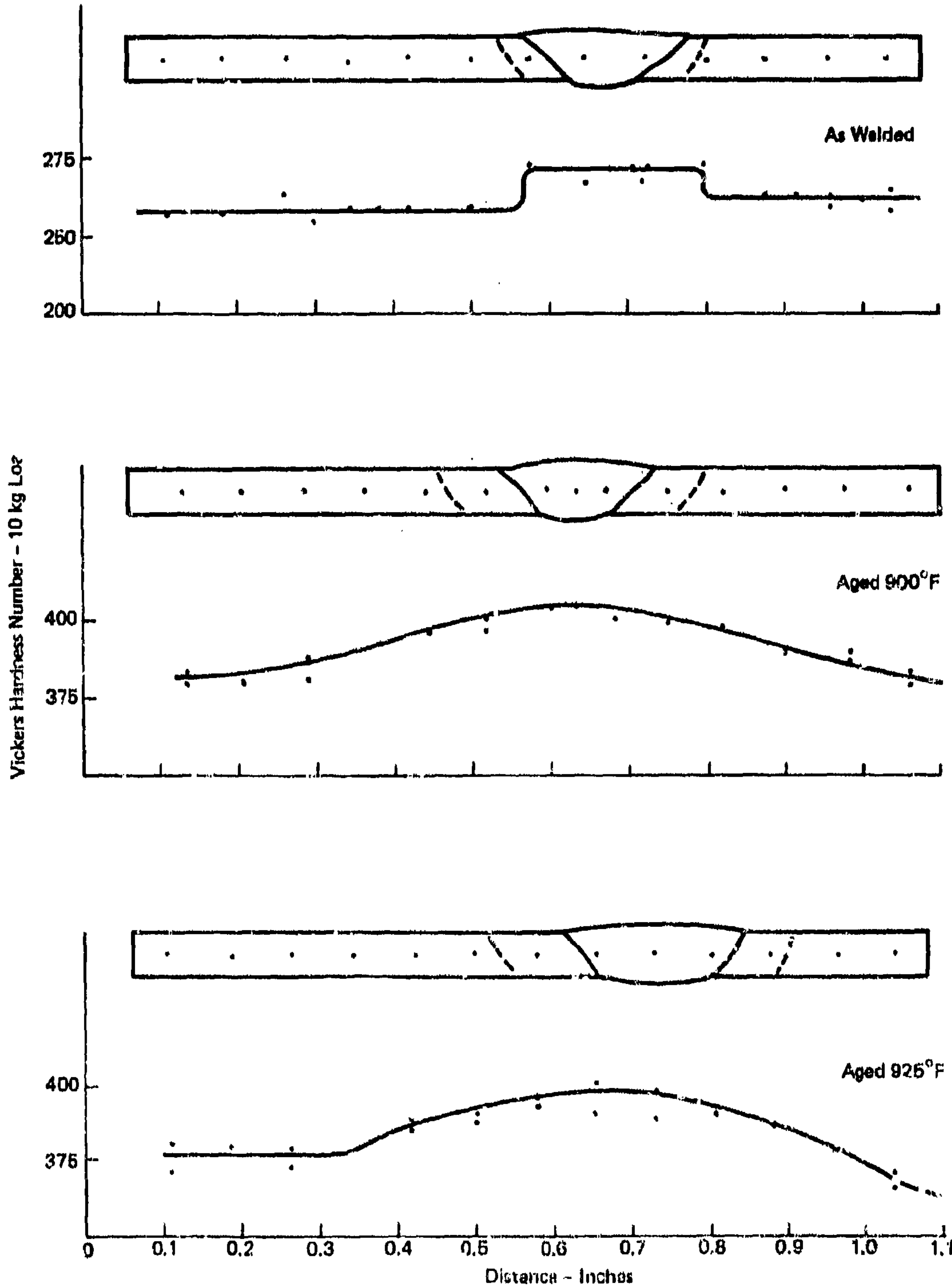
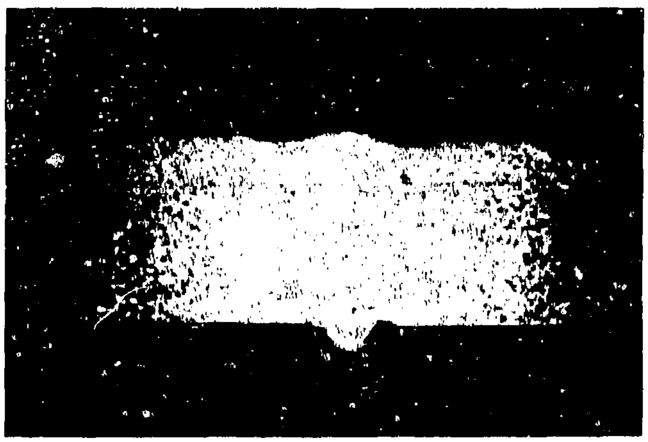


Figure 32. Hardness Surveys of GTA Welds in 0.050 Inch Sheet

As-Welded (10X)



Aged at 900F, 8 Hrs (10X)

Aged at 950F, 8 Hrs (10X)

Figure 33. Macrostructures of Electron Beam Welds in 0.100 in. Solution Annealed Ti-15V-3Cr-3Al-3Sn Sheet

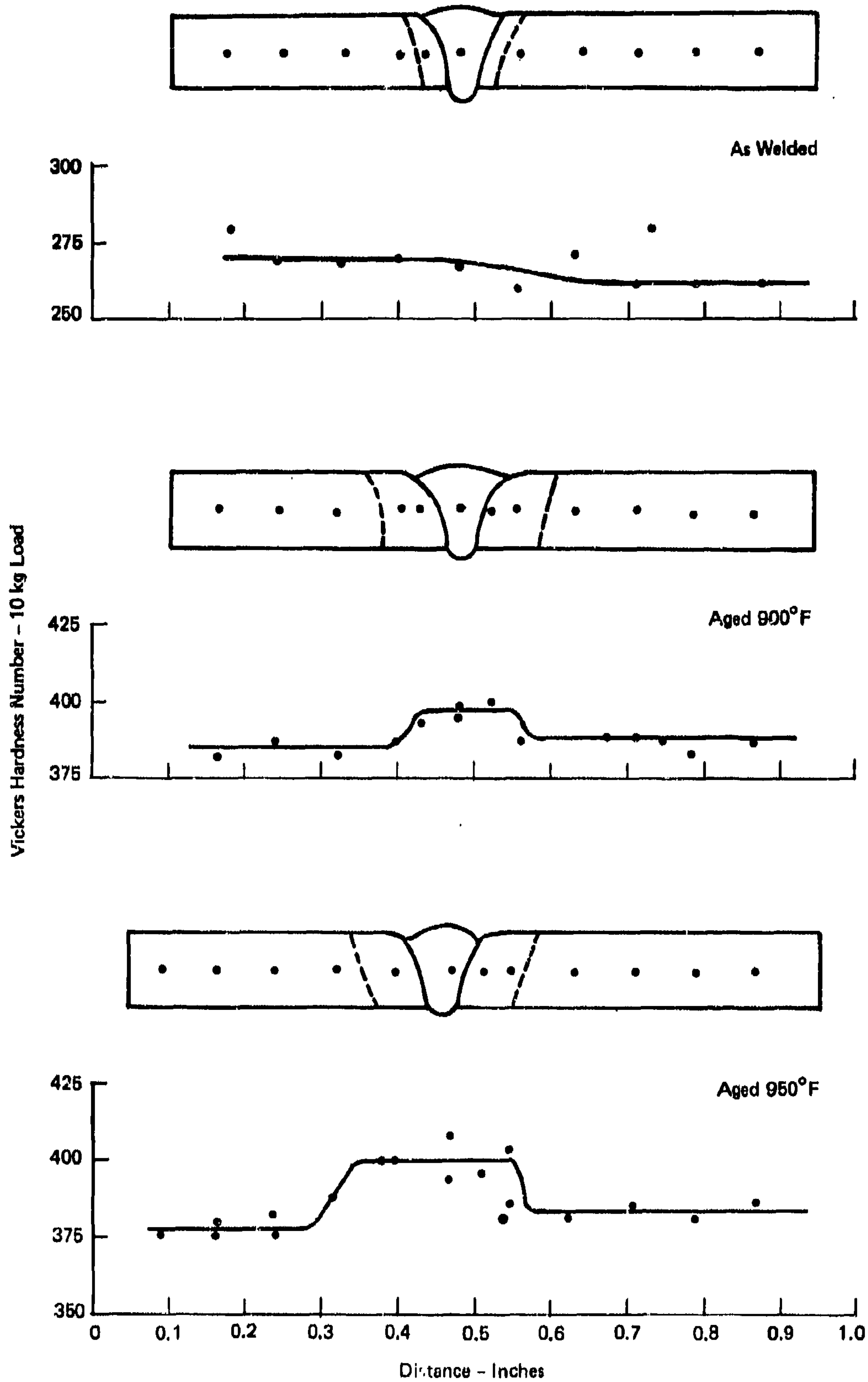
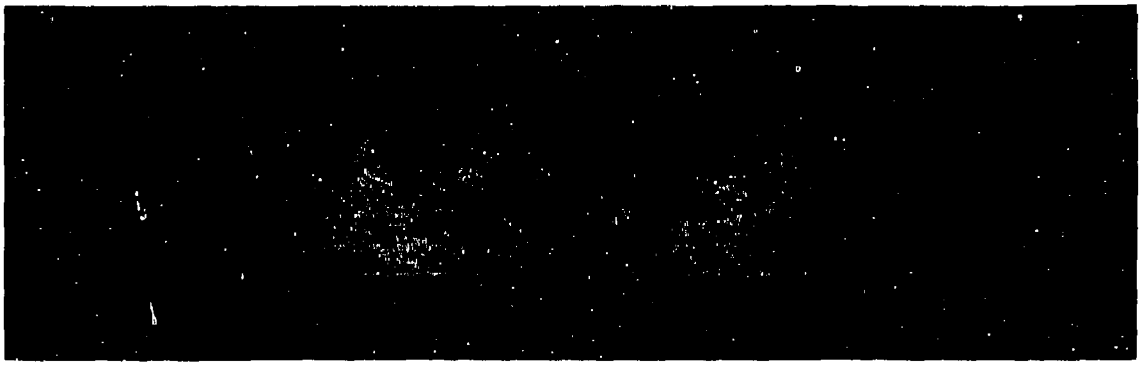
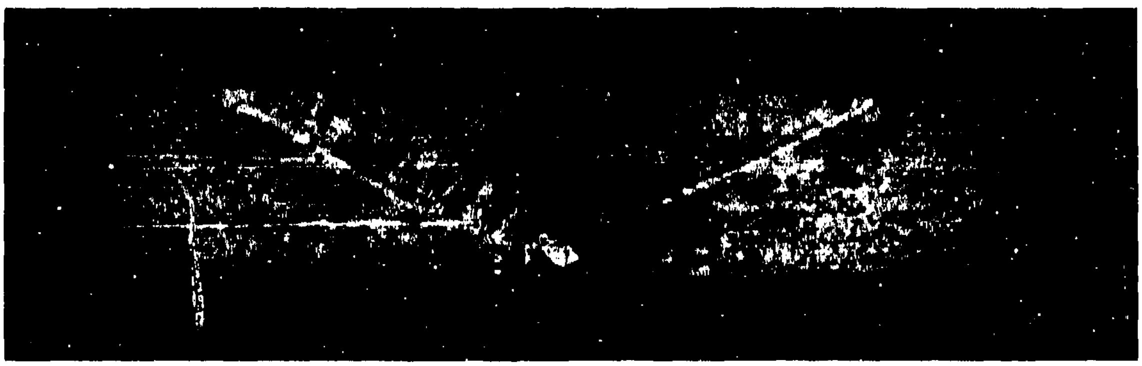


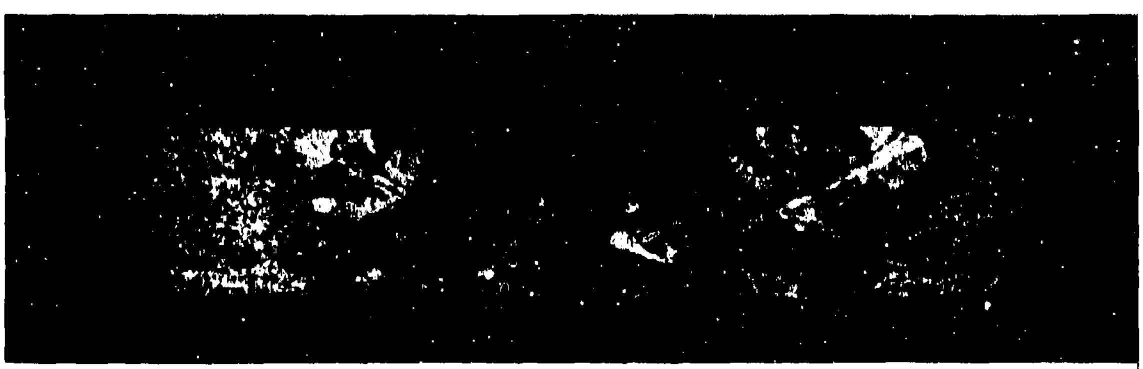
Figure 34. Hardness Surveys of EB Welds in 0.100 Inch Sheet



As-Welded (10X)



Aged at 900F, 8 Hrs (10X)



Aged at 950F, 8 Hrs (10X)

Figure 35. Macrostructures of Gas Tungsten Arc Welds (No Filler) in 0.100 in. Solution Annealed Ti-15V-3Cr-3Al-3Sn Sheet

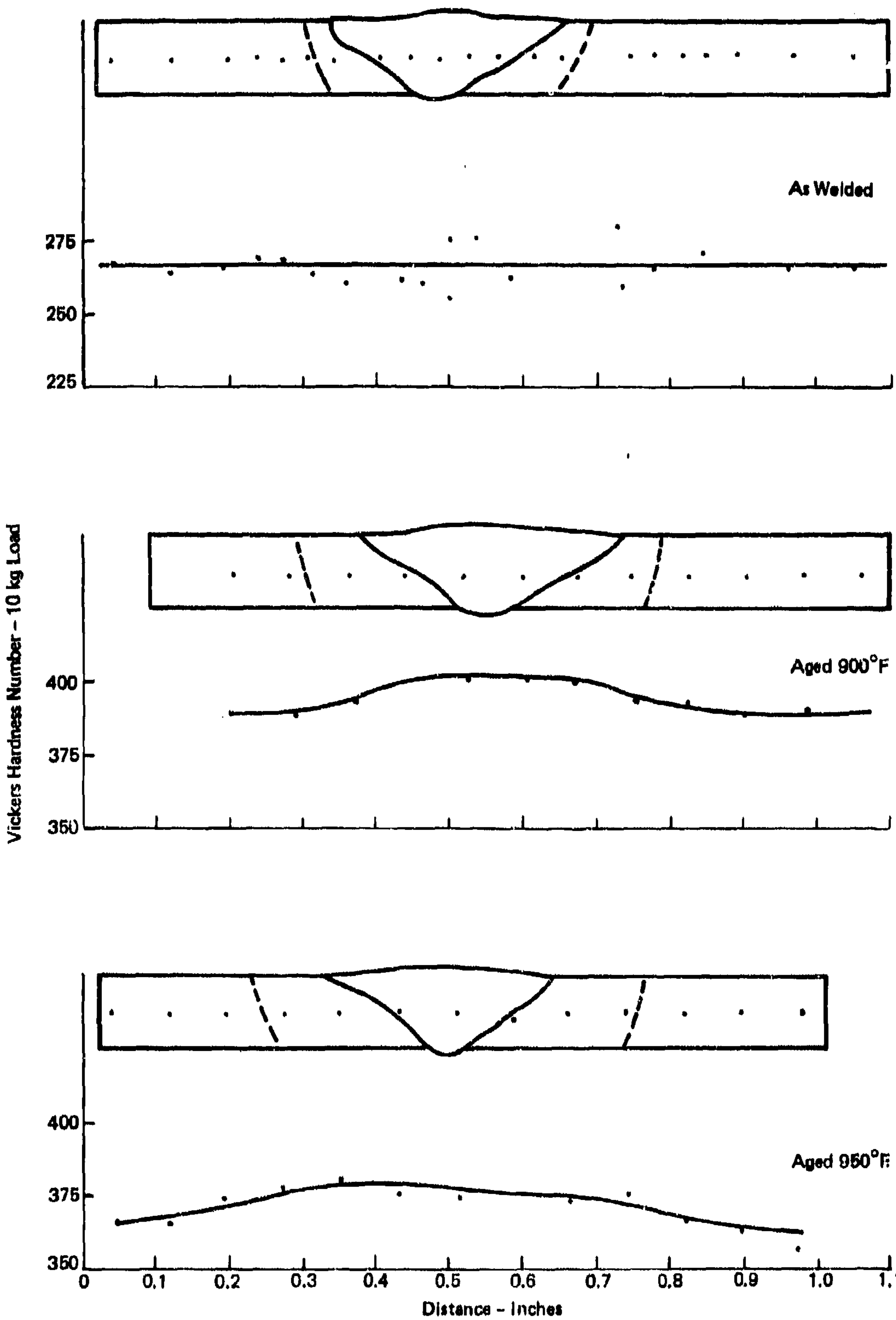
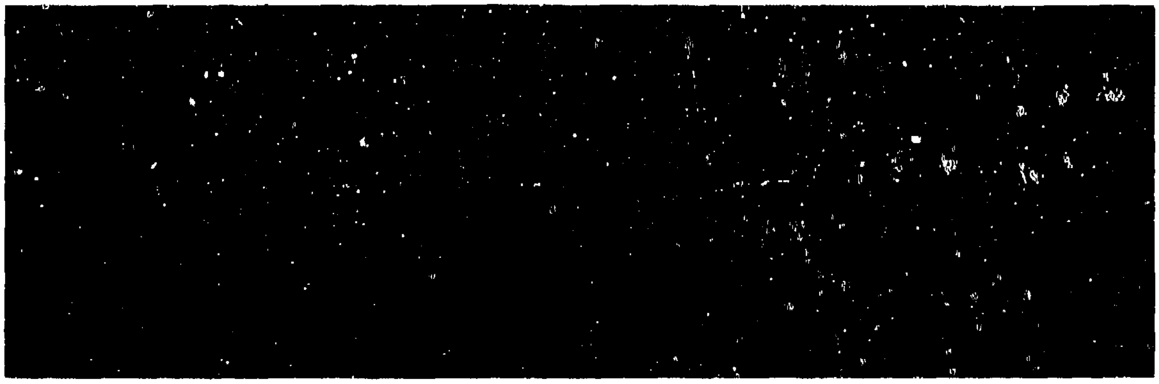
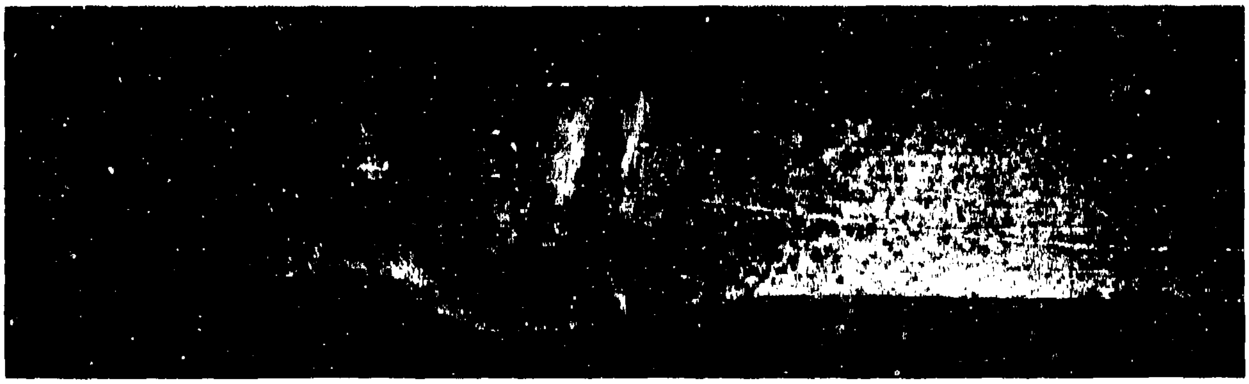


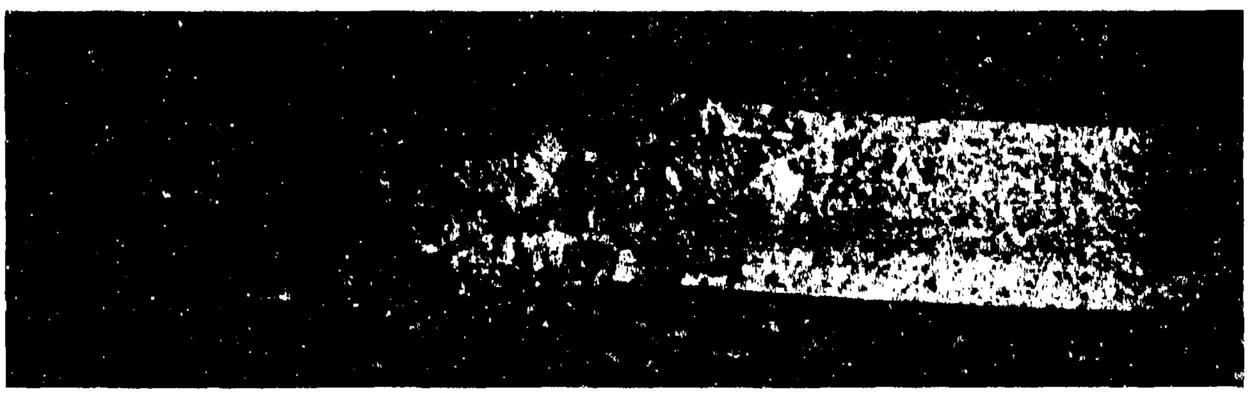
Figure 36. Hardness Surveys of GTA Welds in 0.100 Inch Sheet, No Filler



As-Welded (10X)



Aged at 900F, 8 Hrs (10X)



Aged at 950F, 8 Hrs (10X)

Figure 37. Macrostructures of Gas Tungsten Arc Welds (Filler Added) 0.100 in. Solution Annealed Ti-15V-3Cr-3Al-3Sn Sheet

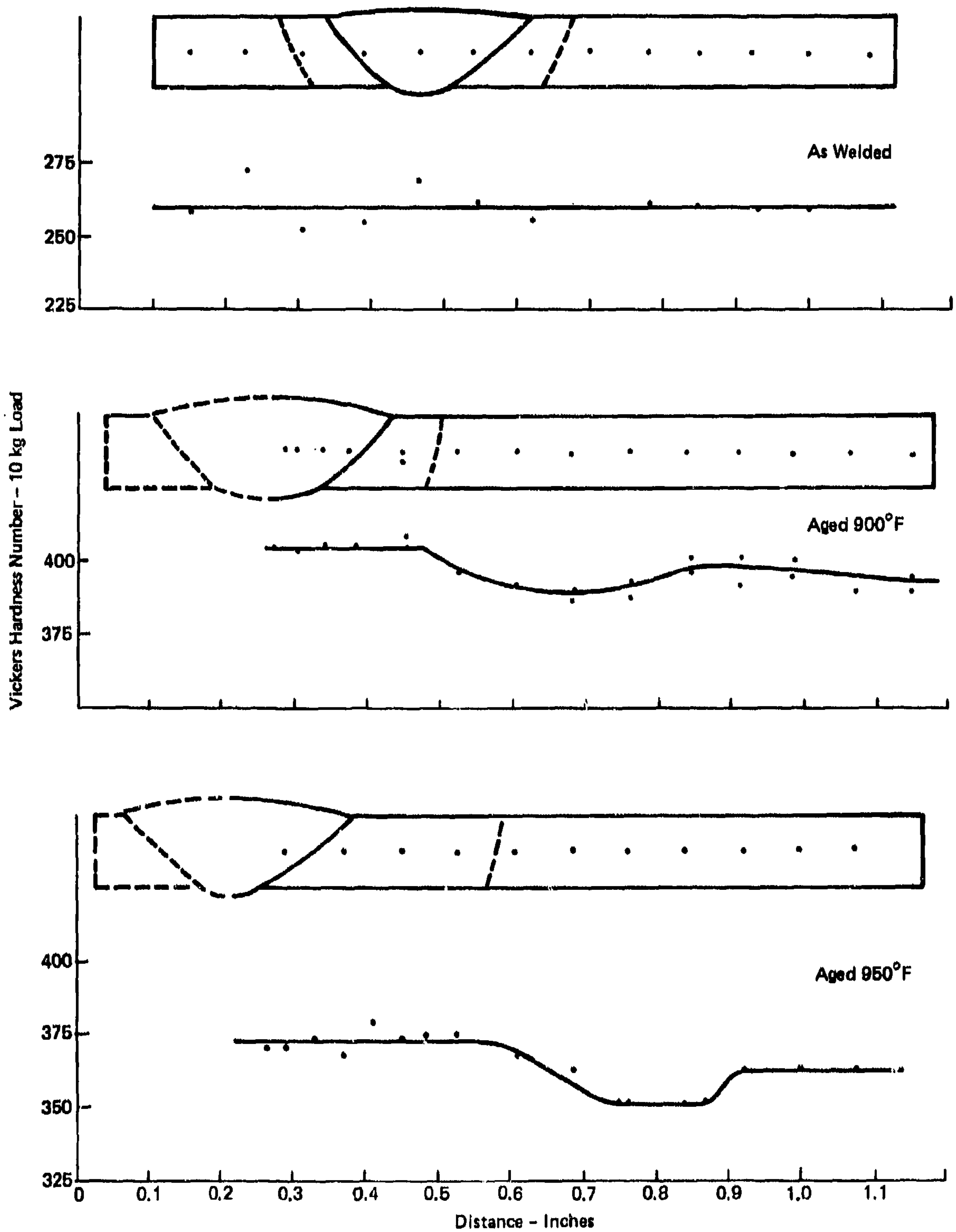
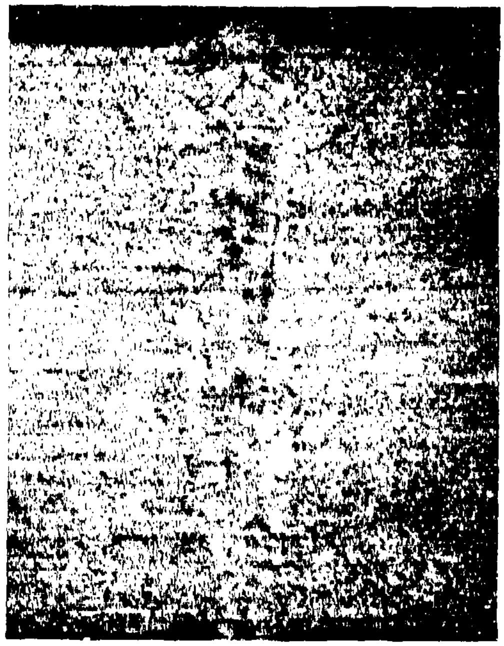
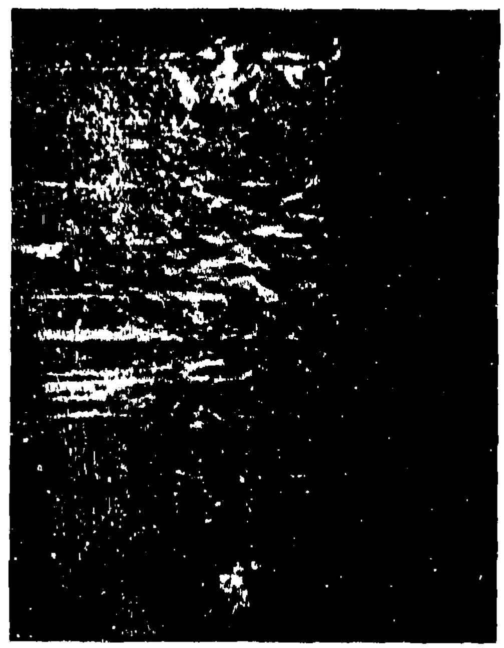


Figure 38. Hardness Surveys of GTA Welds in 0.100 Inch Sheet, Filler Added



As-Welded (10X)

Aged at 900F, 8 Hrs (10X)



Aged at 950F, 8 Hrs (10X)

Figure 39. Macrostructures of Electron Beam Welds in 0.300 in. Solution Annealed Ti-15V-3Cr-3Al-3Sn Plate

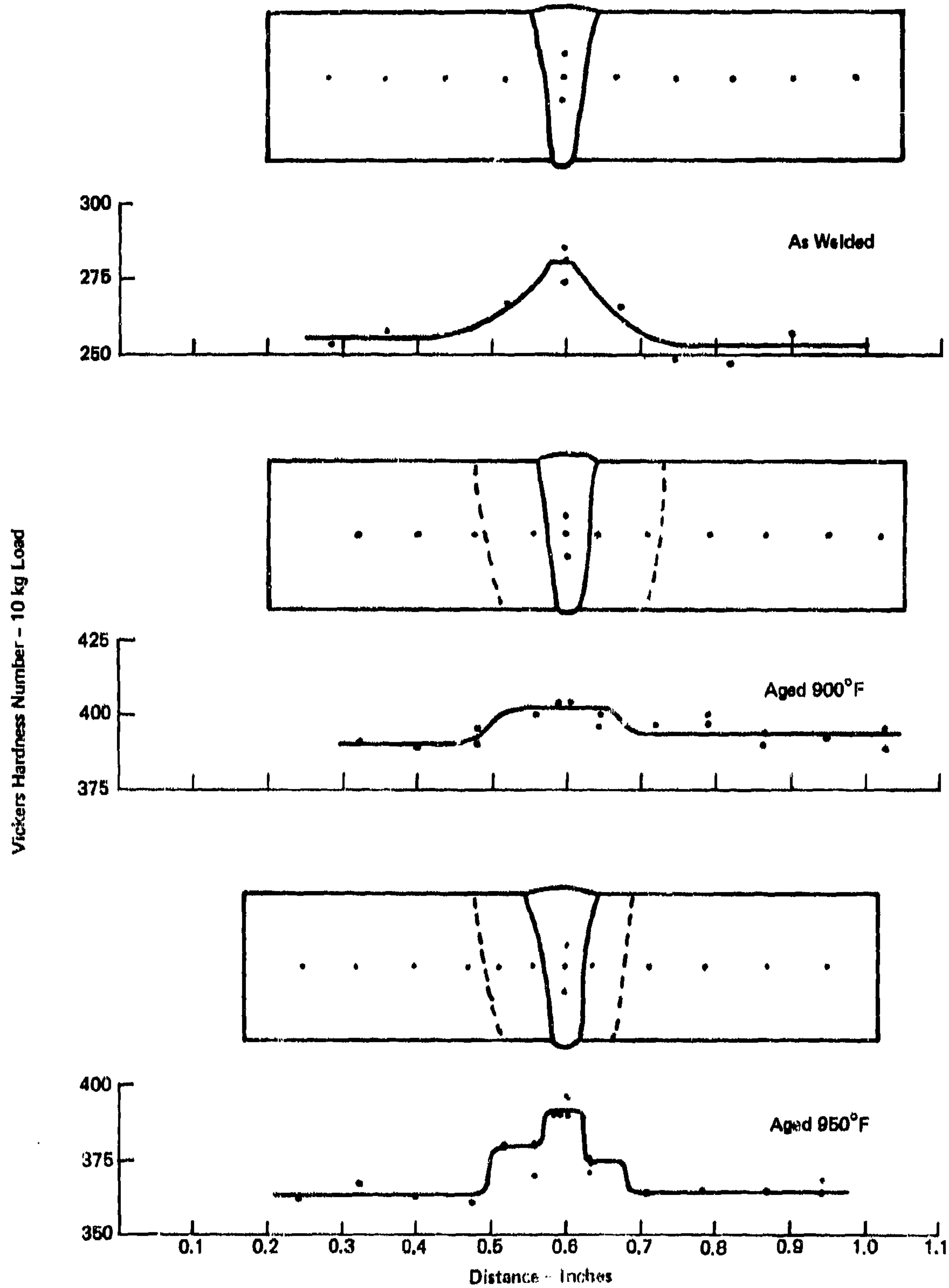
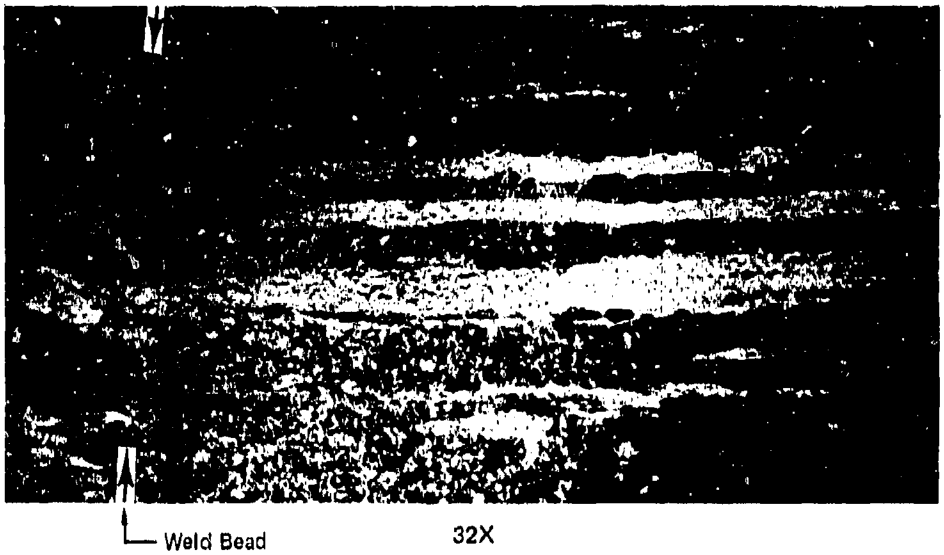


Figure 40. Hardness Survey of EB Welds in 0.300 Inch Plate



32X

100X

Figure 41. Microstructures of Banded Areas in Electron Beam Welded 0.300 in Ti-15V-3Cr-3Al-3Sn Plate (Condition-Aged 900F, 8 Hrs)

SECTION VI
SUMMARY OF RESULTS

The 15V-3Cr-3Al-3Sn alloy was found to be readily weldable in 0.050 inch, 0.100 inch, and 0.300 inch thicknesses by the electron beam and gas-tungsten-arc processes. No tendency for restraint cracking was found (often a fault of heat treatable alloys). The tendency to develop weld porosity is comparable to other weldable titanium alloys such as Ti-6Al-4V and commercially pure titanium – control and elimination depends upon adequate preweld cleaning and control of weld parameters.

Transformation reactions are very sluggish in the Ti-15V-3Cr-3Al-3Sn alloy, which results in soft, ductile (solution treated) weld beads and virtually undetectable heat affected zones in the as-welded condition. Therefore, the optimum sequence for welding is (1) solution treatment, (2) weld, (3) age harden. This produces weld strengths essentially equivalent to base metal and weld ductilities only slightly poorer than base metal. A summary of typical mechanical properties is shown in Figures 42, 43 and 44. Test data indicate that the following specification properties could easily be obtained in weldments of this alloy in gages up to 0.300 inch:

Condition	UTS (ksi)	YS (ksi)	Elong (%)
As welded	125 max	115 max	8 min
As welded and aged	170 min	150 min	-

Test data indicate that notched tensile strength, fracture toughness, and fatigue flow growth rate properties of Ti-15V-3Cr-3Al-3Sn weldments are equivalent, or superior, to Ti-6Al-4V weldments.

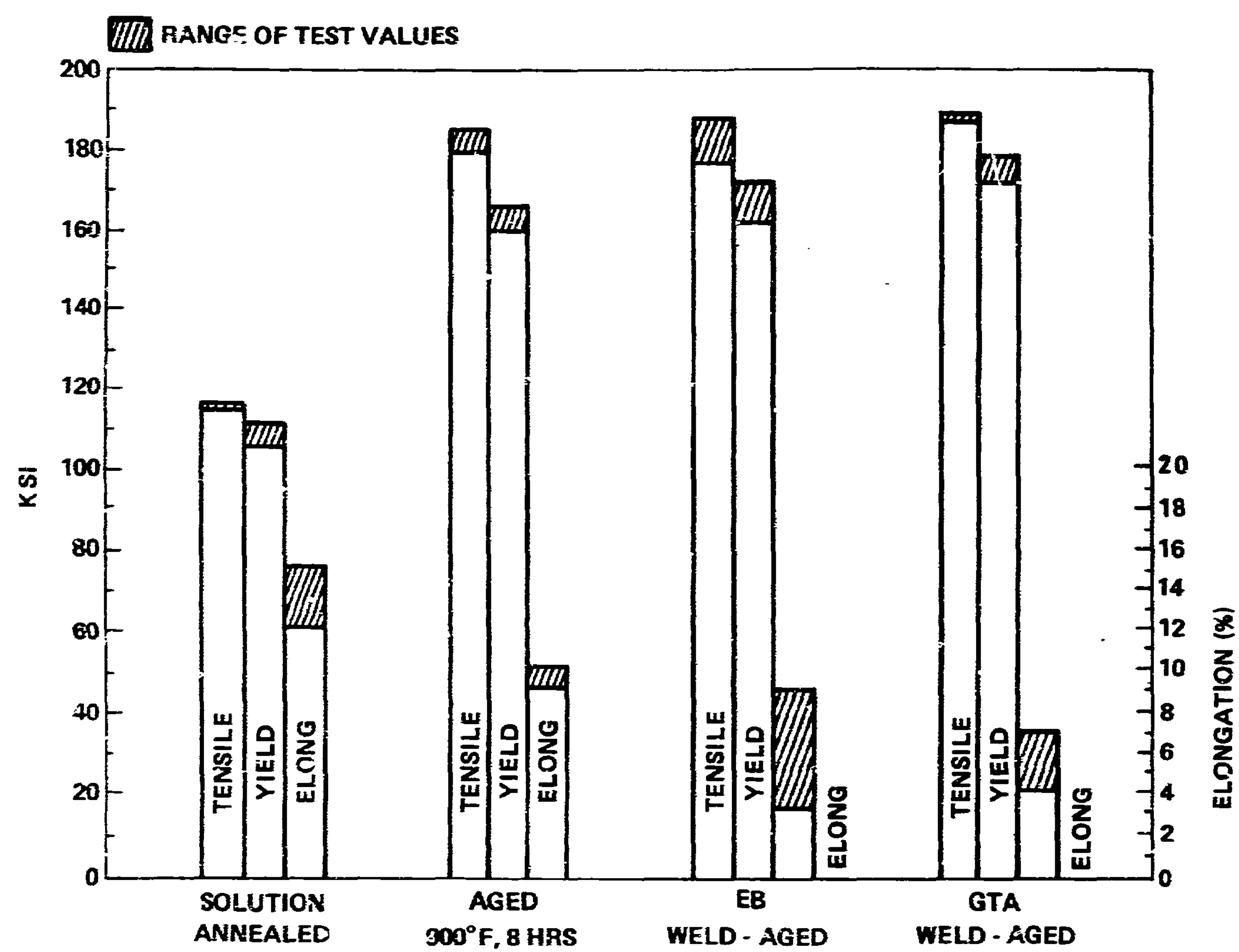


Figure 42. Mechanical Properties of 0.050 in. Ti-15V-3Cr-3A1-3SnParent Material and Weldments

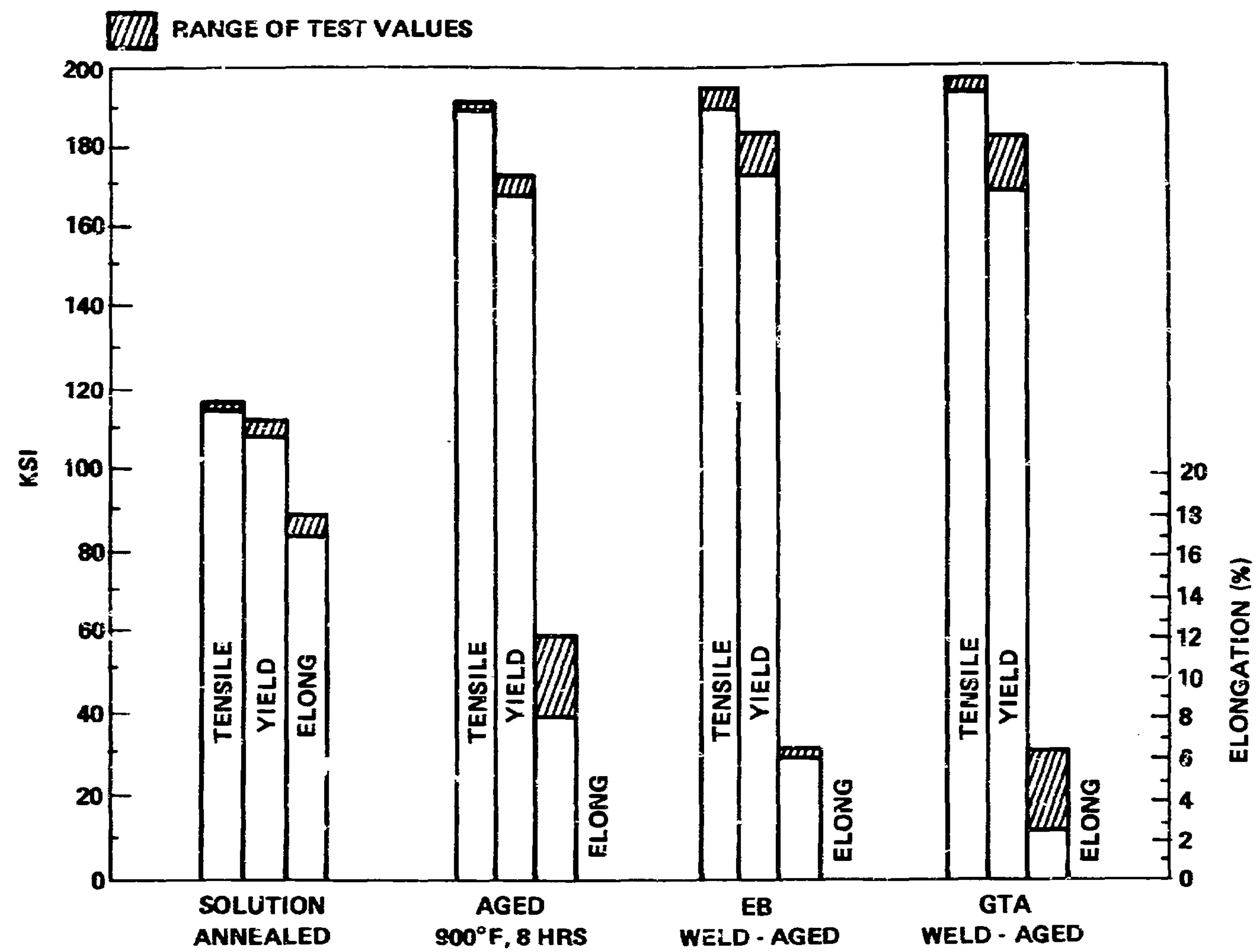


Figure 43. Mechanical Properties of 0.100 in. Ti-15V-3Cr-3Al-3Sn Parent Material and Weldments

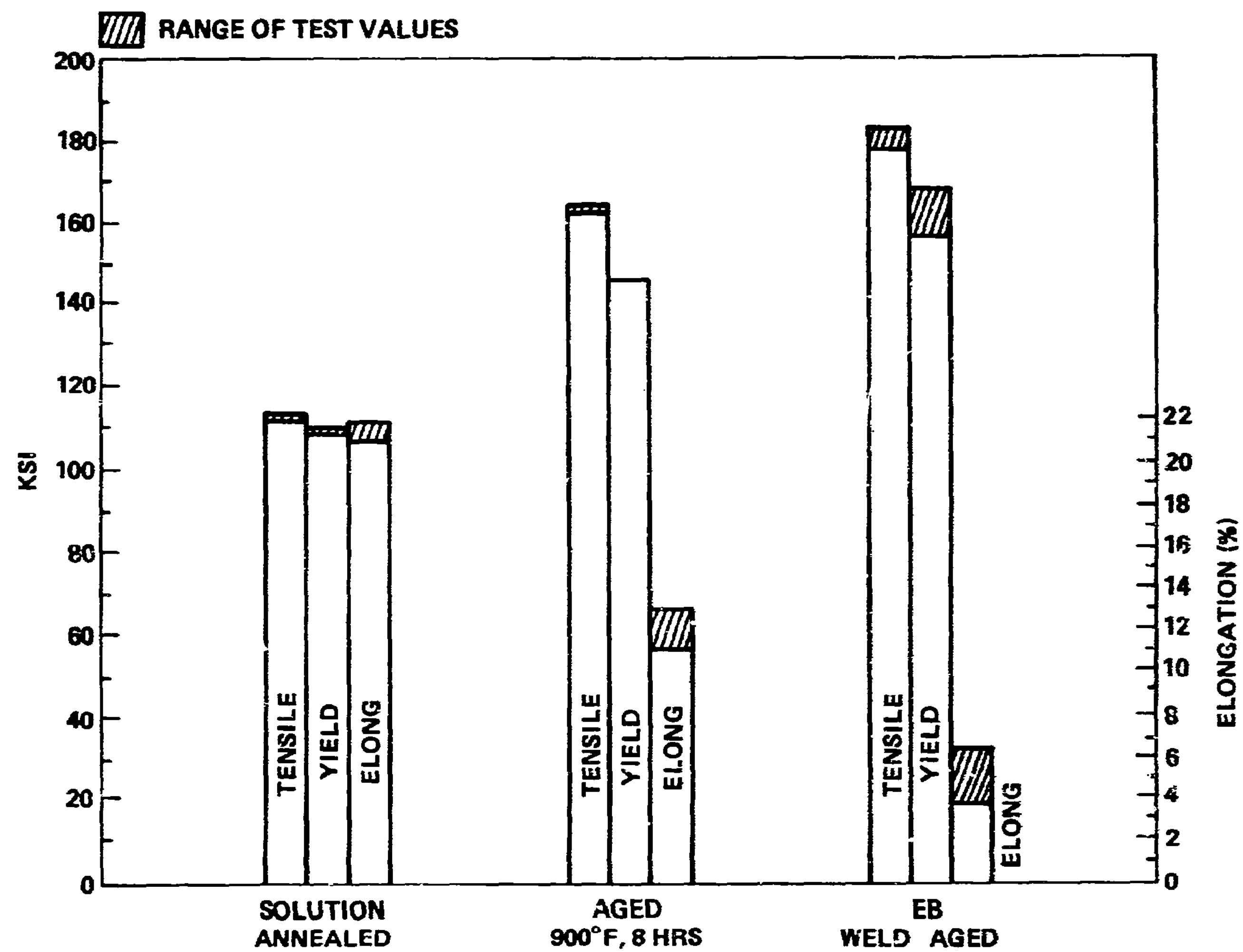


Figure 44. Mechanical Properties of 0.300 in. Ti-15V-3Cr-3Al-3Sn Parent Material and Weldments

SECTION VII
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